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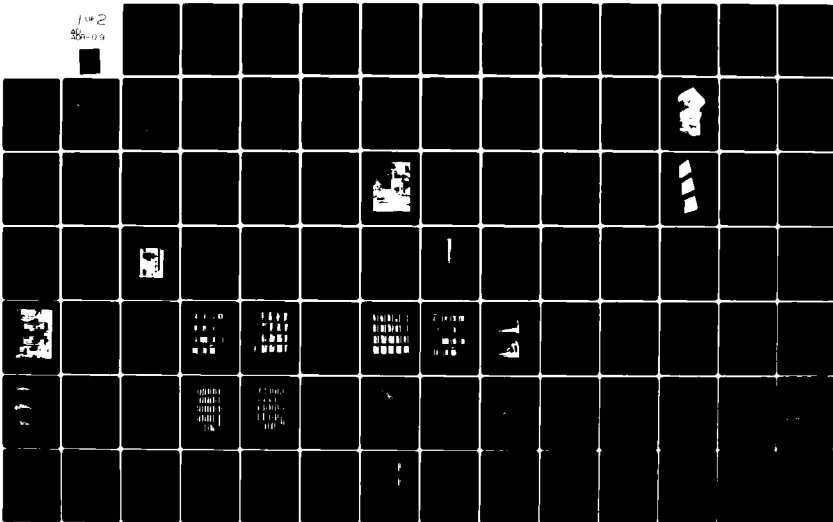

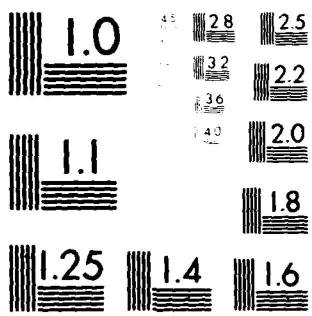

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LOW COST PROCESS FOR MANUFACTURE OF OXIDE DISPERSION STRENGTHENED (ODS) TURBINE NOZZLE COMPONENTS.

General Electric Company
Aircraft Engine Group
Cincinnati, Ohio 45215

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P.G. Bailey

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11 December 1979

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This technical report has been reviewed and is approved for publication.

Robert J Ondercin

Robert Ondercin
Project Manager

For The Director

H. A. Johnson

H. A. Johnson
Chief, Metals Branch
Manufacturing Technology Division

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This final technical report describes a program for producing low cost processes for the manufacture of Oxide Dispersion Strengthened (ODS) turbine nozzle components.

The processes established in this program will demonstrate that high pressure turbine vanes, low pressure turbine vanes and high pressure turbine bands can be manufactured from near-net shape components via directional forging and forge bending.

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20. Abstract (Cont.)

Near-net shape processes, manufacturing processes, mechanical property test results, and cost analysis are described.

The technology developed in this program is currently being applied to turbine nozzle components for the F404 engine.

FOREWORD

This final technical report covers the work performed under Contract F33615-76-C-5235 from 30 June 1976 to 31 December 1979.

This contract with the Aircraft Engine Group, General Electric Company, Cincinnati, Ohio, was initiated under Manufacturing Methods Project No. 855-6, "Low Cost Processes for Manufacture of Oxide Dispersion Strengthened (ODS) Turbine Nozzle Components." The work was administered under the technical direction of Captain Robert Schafrik, Captain John Tanzola and Mr. Robert Ondercin of the Metals Branch (LTM), Manufacturing Technology Division, Air Force Materials Laboratory, Wright-Patterson Air Force Base, Ohio.

The program was conducted by the Material and Process Technology Laboratories of the General Electric Company, Cincinnati, Ohio. The program was conducted under the direction of Mr. E. J. Kerzicnik, Program Manager and Mr. P. G. Bailey, Technical Manager, with Mr. R. J. Perkins and Mr. J. A. Stahl serving as the Principal Investigators on the program.

TRW Inc., Cleveland, Ohio was a major subcontractor for the near-net shape effort with Mr. D. J. Moracz as program engineer and Mr. C. R. Cook program manager. Solar Division of International Harvester, San Diego, California was an additional subcontractor on the program. The work at Solar was under the direction of Mr. F. K. Rose. Special Metals and Huntington Alloys supplied ODS material for the program.

This project was accomplished as part of the Air Force Manufacturing Methods Program, the primary objective of which is to implement, on a timely basis, manufacturing processes, techniques, and equipment for use in economical production of USAF materials and components.

Your comments are solicited on the potential utilization of the information contained herein as applied to your present and or future production programs. Suggestions concerning additional manufacturing methods development required on this or other subjects will be appreciated.

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SECTION I

INTRODUCTION

Oxide dispersion strengthened (ODS) alloys are very attractive for use as turbine vane materials because, in comparison with conventional superalloys, they offer greater strength and creep resistance at high temperatures, have higher melting points, and are microstructurally stable nearly to their melting points. In certain cases, these alloys have the ability to operate without protective coatings.

Use of ODS alloys can provide significant savings in fuel consumption through reduction or elimination of the cooling air required with cast vanes; however, a problem that has discouraged more widespread application of ODS alloys has been their continued high cost. The major cost contributor is the low yield of finished parts from state-of-the-art rectangular cross section extrusions. The current material utilization factor is about 8% as depicted in Figure 1.

This program was directed at the establishment of low cost processes for turbine nozzles fabricated from ODS alloys. The processes included large unit, high yield methods for primary preforms, near-net shape (NNS) secondary working, and an assessment of improved machining processes for low pressure turbine (LPT) vanes, high pressure turbine (HPT) vanes, and HPT band segments for the F101 engine. The primary intent in this program is to produce near-net shapes (NNS) for better material utilization at low additional cost. A NNS is defined in this program as final part configuration with a material envelope of approximately 0.050 inch thickness. It is estimated that NNS result in material savings of about 50%.

Subcontractors in the program were chosen for their expertise in ODS technology. Special Metals and Huntington Alloys, the preform suppliers, have produced commercial ODS alloys for the F101 engine and are active in advanced ODS alloy development. Both TRW and Solar, the secondary-shape vendors, have had experience with ODS alloys and extensive experience in aircraft part shape working.

Processes evaluated included directional forging carried out by TRW and isothermal shape rolling (ISR) by Solar. Both processes were utilized for HPT vanes, while forge bending was used for the LPT vanes and HPT bands. The feasibility of plate rolling and forge bending was determined under a previous NASA program (1). Initial forging experiments were also conducted in this program. The program was divided into three phases:

- Phase I — Establish ODS alloy near-net shape forging process for HPT vanes and select one ODS alloy (MA754).
- Phase II — Establish ODS alloy near-net shape processes for LPT vanes, HPT bands and demonstrate reproducibility of the HPT vane process developed in Phase I. Investigate isothermal shape vane rolling.
- Phase III — Establish final manufacturing processes for producing low cost ODS alloy turbine nozzle vane and band segments using processes established in Phase I and Phase II. Evaluate components produced in the program in engine testing.

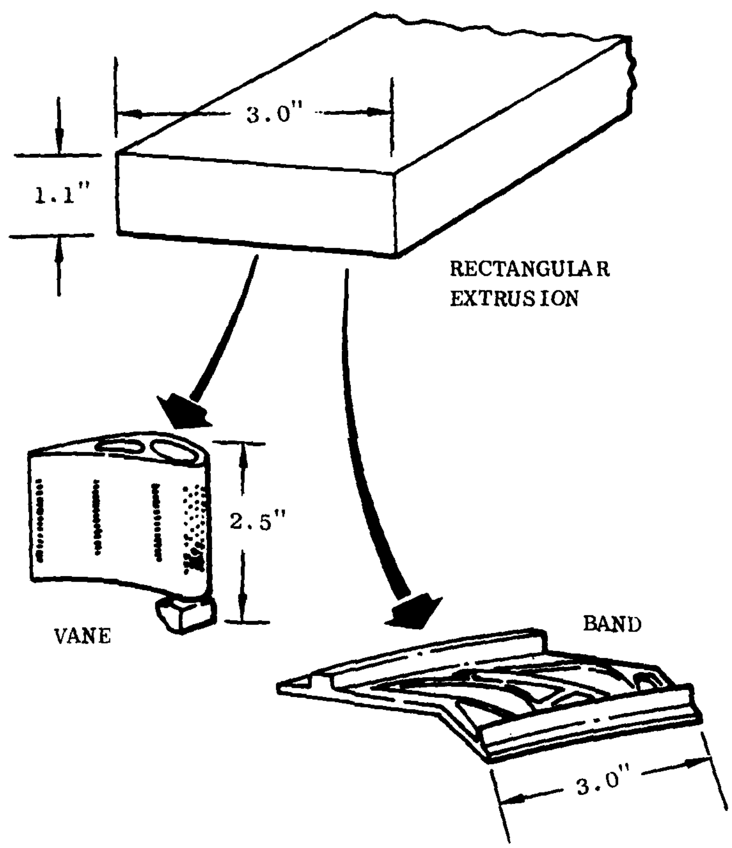


Figure 1. Current Component Manufacturing Method

SECTION II

SUMMARY

Near-net shape (NNS) processes were established for secondary working of oxide dispersion strengthened MA754 for aircraft turbine nozzle components. These processes were shown capable of maintaining required microstructures and properties for the vane and band applications.

The program was initiated with the ODS NiCrAl alloys MA757 and YDNiCrAl. Because of unfavorable engine test experience in a concurrent program, the alloy for this program was changed to MA754, an ODS NiCr alloy.

Of the secondary working processes evaluated, directional forging of HPT vanes and plate bending for LPT vane and HPT bands were determined to be the most cost effective NNS processes for those ODS turbine components. These processes are shown schematically in Figures 2, 3 & 4.

Preforms established for the program were standard rectangular bar cut on the diagonal for forging stock and hot rolled plate for bending stock. Originally, extruded kidney shapes had been planned as preforms but they could not be produced with suitable microstructures.

Material cost savings of 50 to 60% and machining cost savings of 20 - 30% are projected for the NNS process compared with the current manufacturing procedures which involve machining from rectangular bar. MA754 was the final selection for the near-net shape process evaluation including HPT vanes, LPT vanes and HPT inner bands.

Engine testing of near-net shape low pressure turbine vanes of ODS alloy MA754 was successfully conducted in an F101 engine. Comparison with previously run vanes manufactured by current processes showed no discernable differences except in the manner of oxide buildup. This difference is attributed to the prior oxidation of the conventional vanes which behaved differently than the newly machined surfaces of the near-net shape vanes.

Installation of the near-net vanes in an existing nozzle provided an opportunity to successfully try out a potential vane repair process, which comprised EDM removal and braze replacement of vanes.

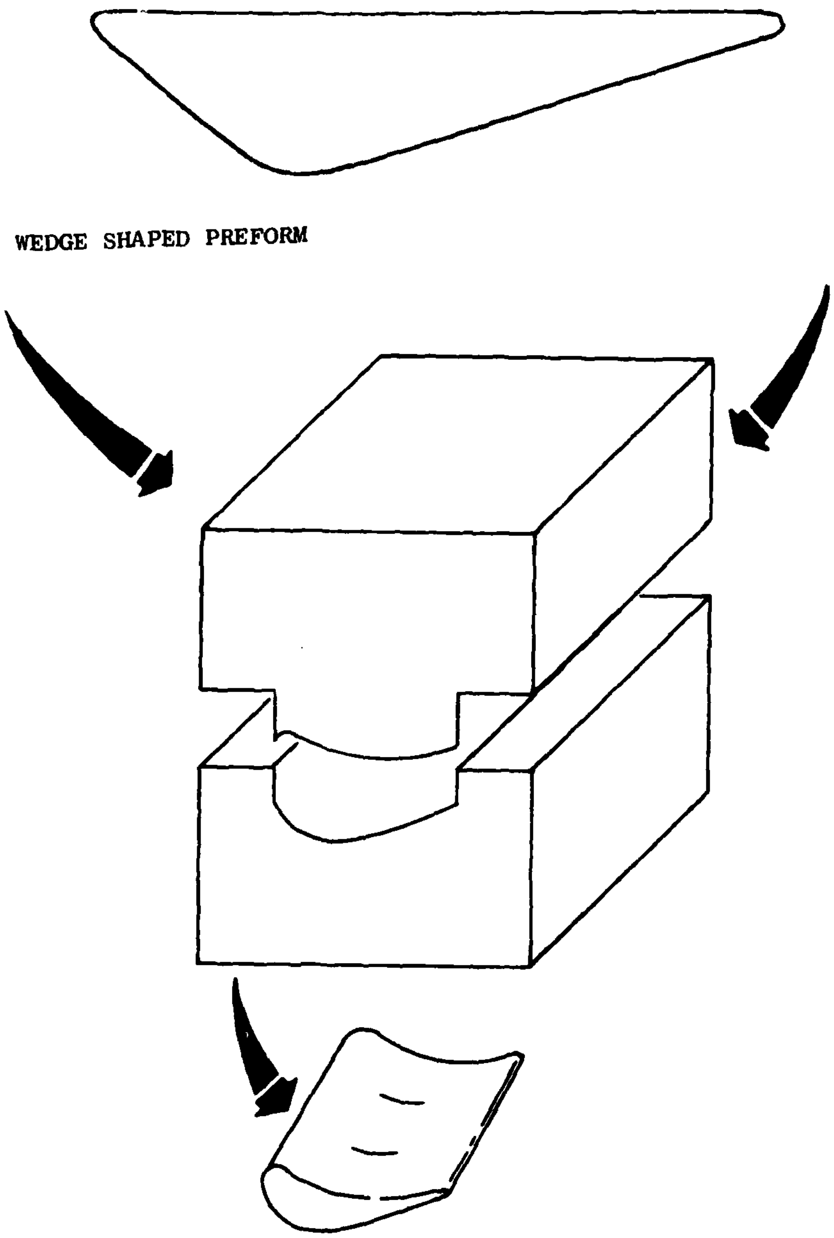


Figure 2. ODS Alloy HPT Vane Forge Process

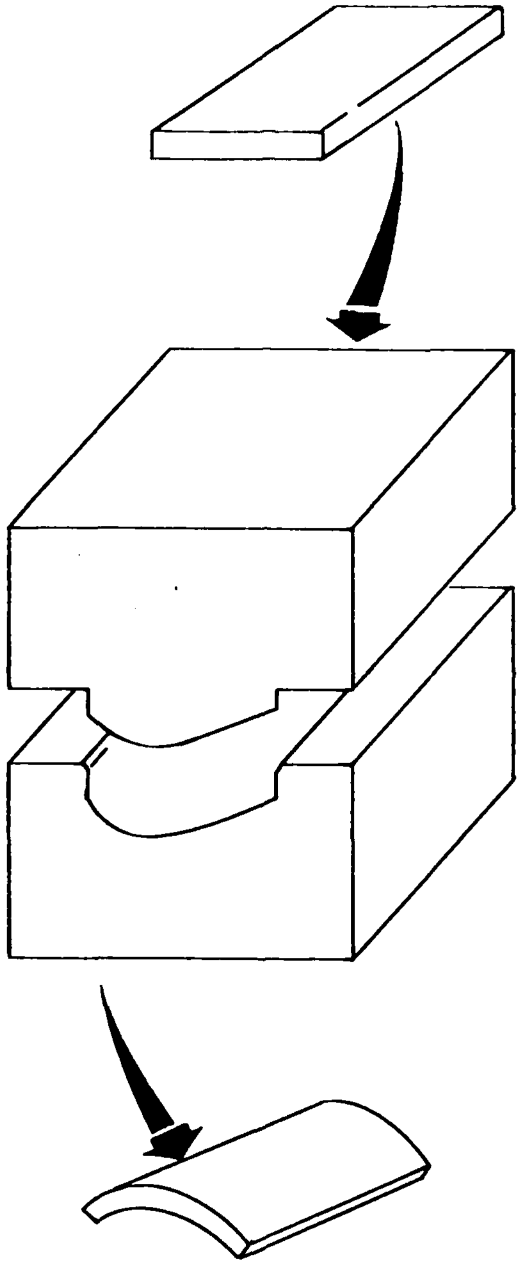


Figure 3. ODS Alloy LPT Vane Net Shape Plate Bending Process

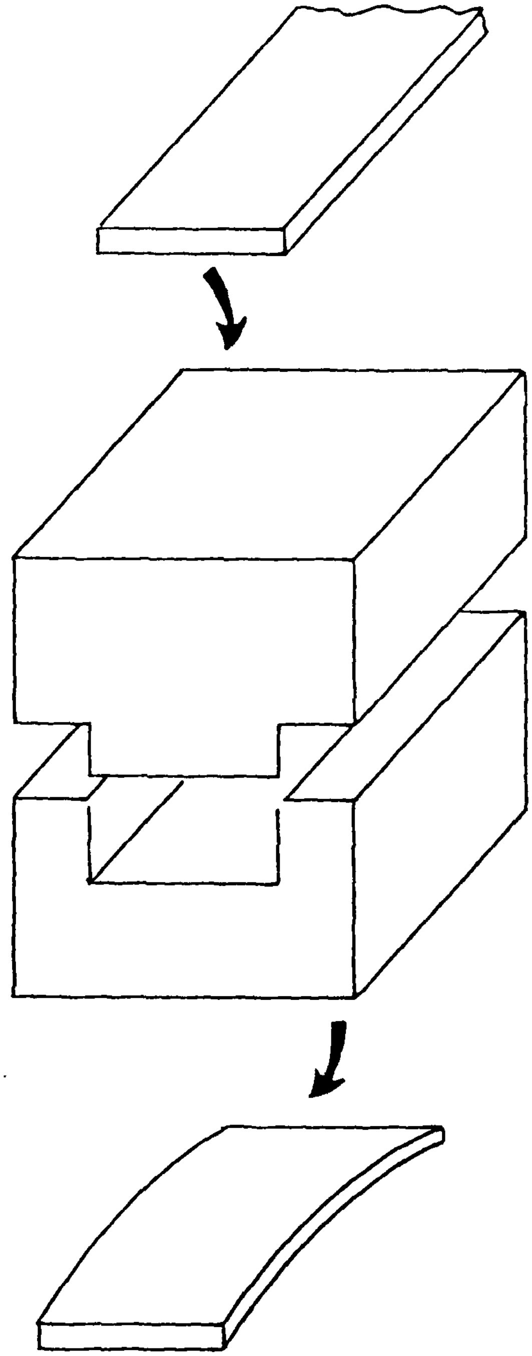


Figure 4. ODS Alloy HPT Bands Near Net Shape Process

SECTION III

NEAR-NET SHAPE PROCESSES

3.1 MATERIAL SELECTION

Initially, three candidate ODS alloys were chosen for the program. Their compositions and suppliers are shown in Table 1. MA754 is the alloy currently being used for several engine turbine nozzle components. MA757 and YDNiCrAl were developed to be more oxidation resistant than MA754 by virtue of a 4% aluminum addition.

During the course of the 1st phase of the program, as part of a concurrent program, an F101 HPT nozzle containing YDNiCrAl, MA754 and 8077 (which is very similar to MA757) conventionally machined vanes was engine run and evaluated. The YDNiCrAl and 8077 vanes exhibited more severe cracking, trailing edge bowing and greater oxidation and hot corrosion deterioration than did the MA754.

The above test results and another similar General Electric test essentially removed the ODS NiCrAl alloys from further consideration as turbine vanes in this program. The engine test results and the loss of texture in the YDNiCrAl wedge shaped preform forging dictated the MA754 material selection for the second forging campaign.

3.2 PROCESS SELECTIONS

Based upon process feasibility demonstrations in a previous program, (1) directional forging was selected for processing HPT vanes. Plate rolling, followed by forge bending was selected for LPT vanes and HPT bands.

3.3 TOOLING DESIGNS

3.3.1 LPT Vane Tooling

The LPT vane plate bending tooling used for NNS processing had been adapted by TRW from tooling previously designed for use on a NASA contract (1). Tooling design is shown in Figure 5. Width tolerances were narrowed to insure that each formed plate would be identical in shape i.e. the starting plate width is the same as the die cavity width with allowances only for thermal expansion. Correlation of widths allowed for positive preform location. The tooling designs shown in the figures were used in Phase II to produce NNS LPT vanes for engine testing.

3.3.2 HPT Band Tooling Design

Tooling was designed with the intent to produce a near-net shape band. The following considerations were made: (a) a 0.050-inch envelope was allowed for the thickness dimension, (b) a 0.100-inch envelope was allowed for length and width dimensions, and (c) the tooling was designed for the inner band curvature. Tooling designs in Figure 6 allowed for electrical resistance heating to minimize heat loss. The tooling shown was used to produce NNS inner bands for Phase II of the program.

TABLE 1

PROGRAM MATERIALS

Material Designation	Supplier	Nominal Composition, w/o
MA 754	Huntington Alloys	Ni-20Cr-0.3Al-0.5Ti-0.6Y_2O_3
MA 757	Huntington Alloys	Ni-16Cr-4Al-0.5Ti-0.6Y_2O_3
YD NiCrAl	Special Metals	Ni-16Cr-4Al-1Y_2O_3

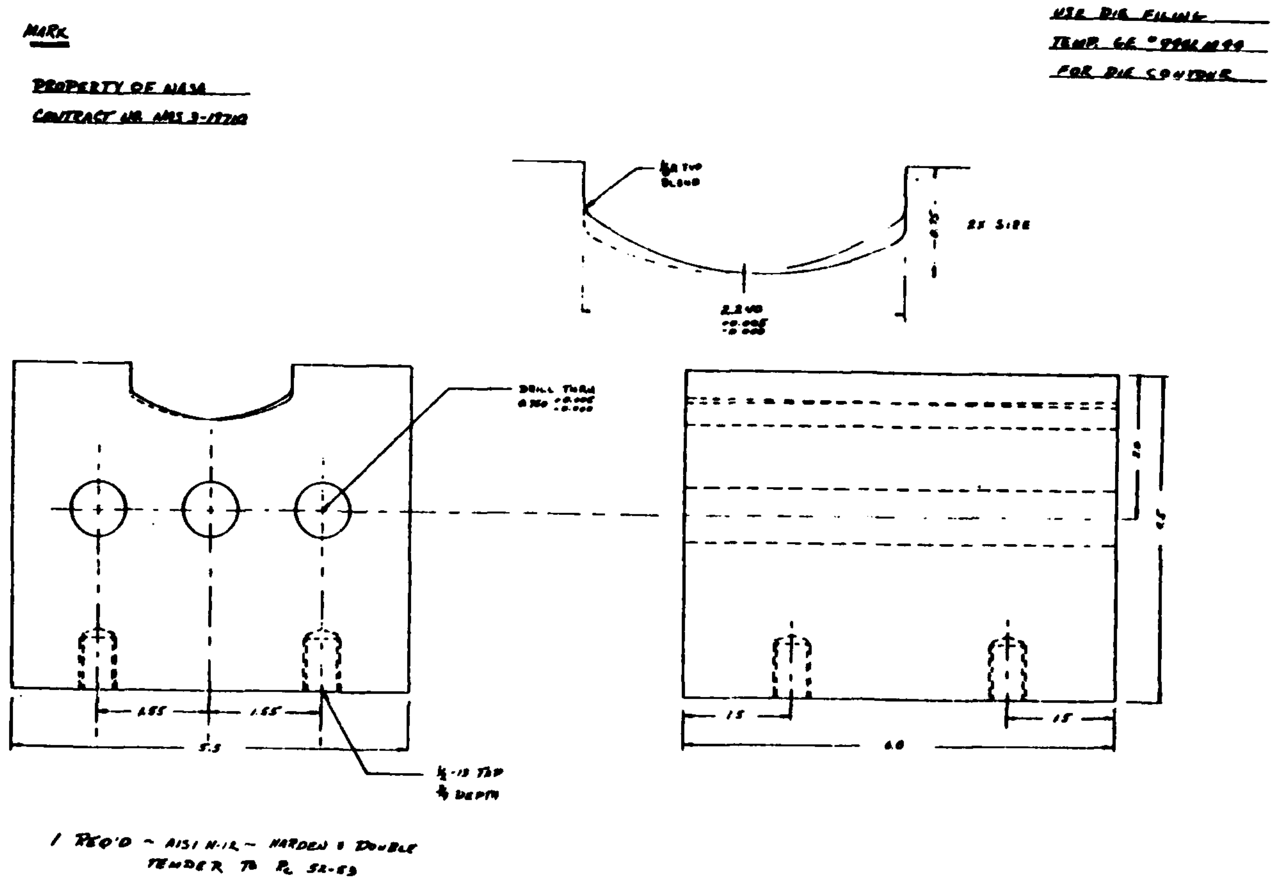


Figure 5. LPT Vane Forming Tooling Design

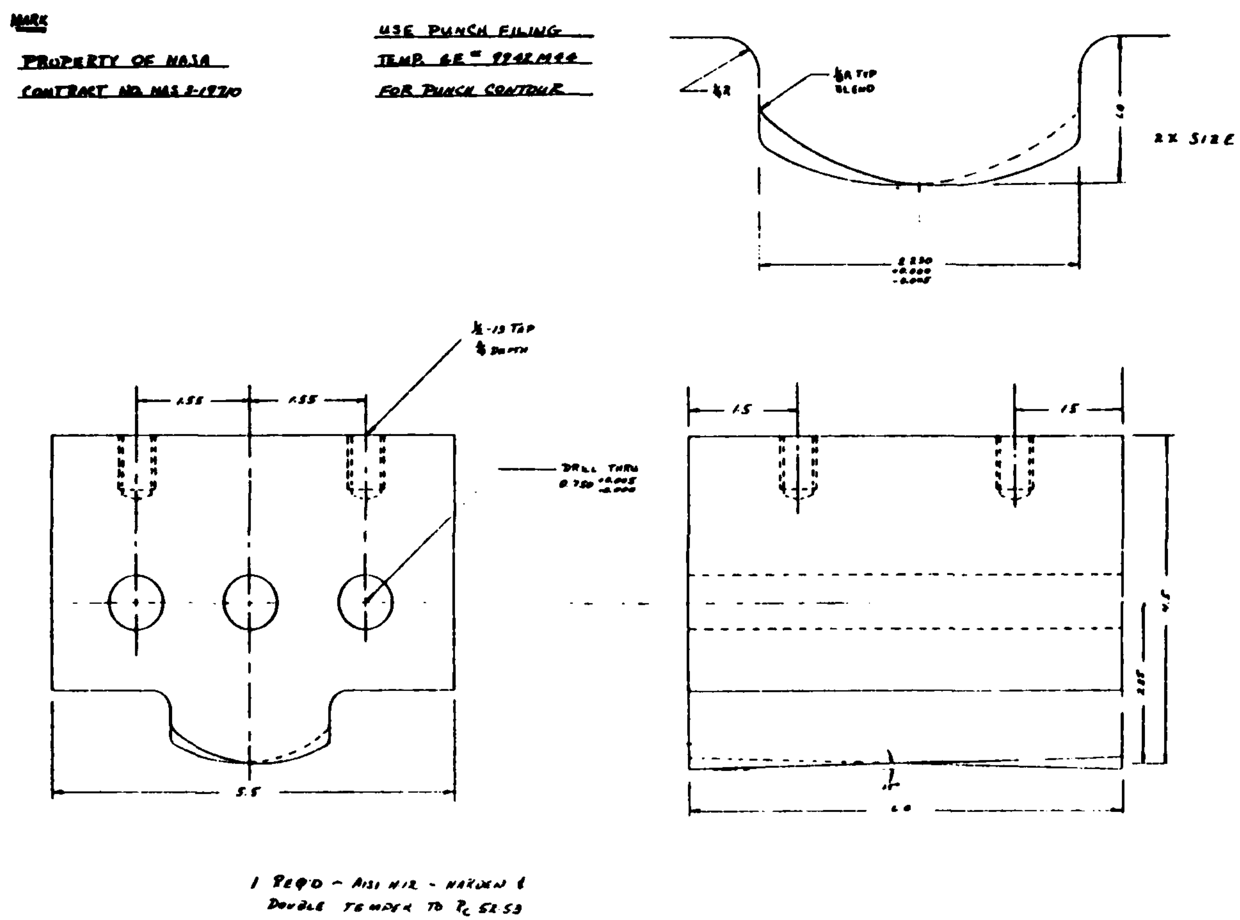


Figure 5. (Continued)

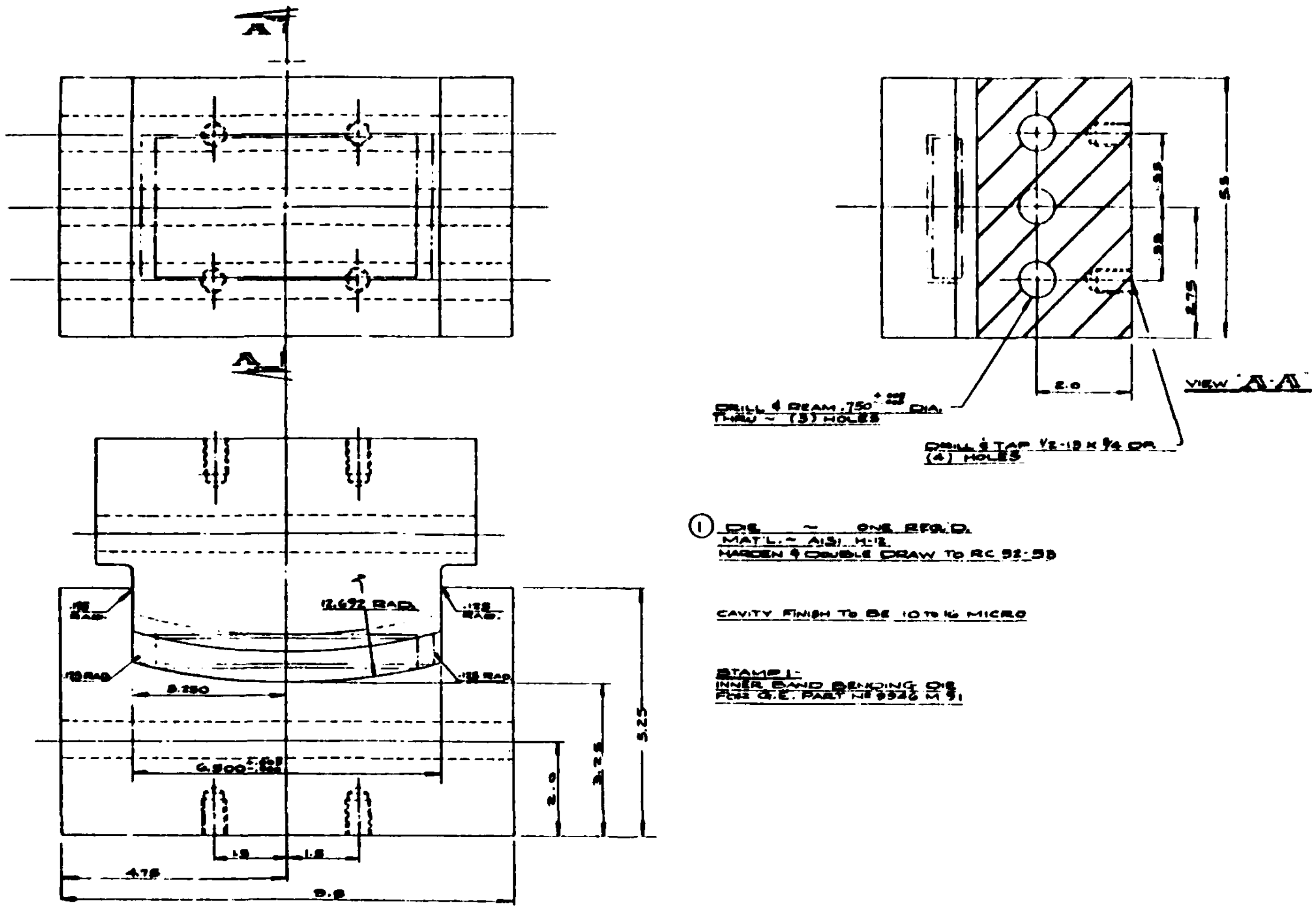


Figure 6. HPT Band Forming Tooling Design

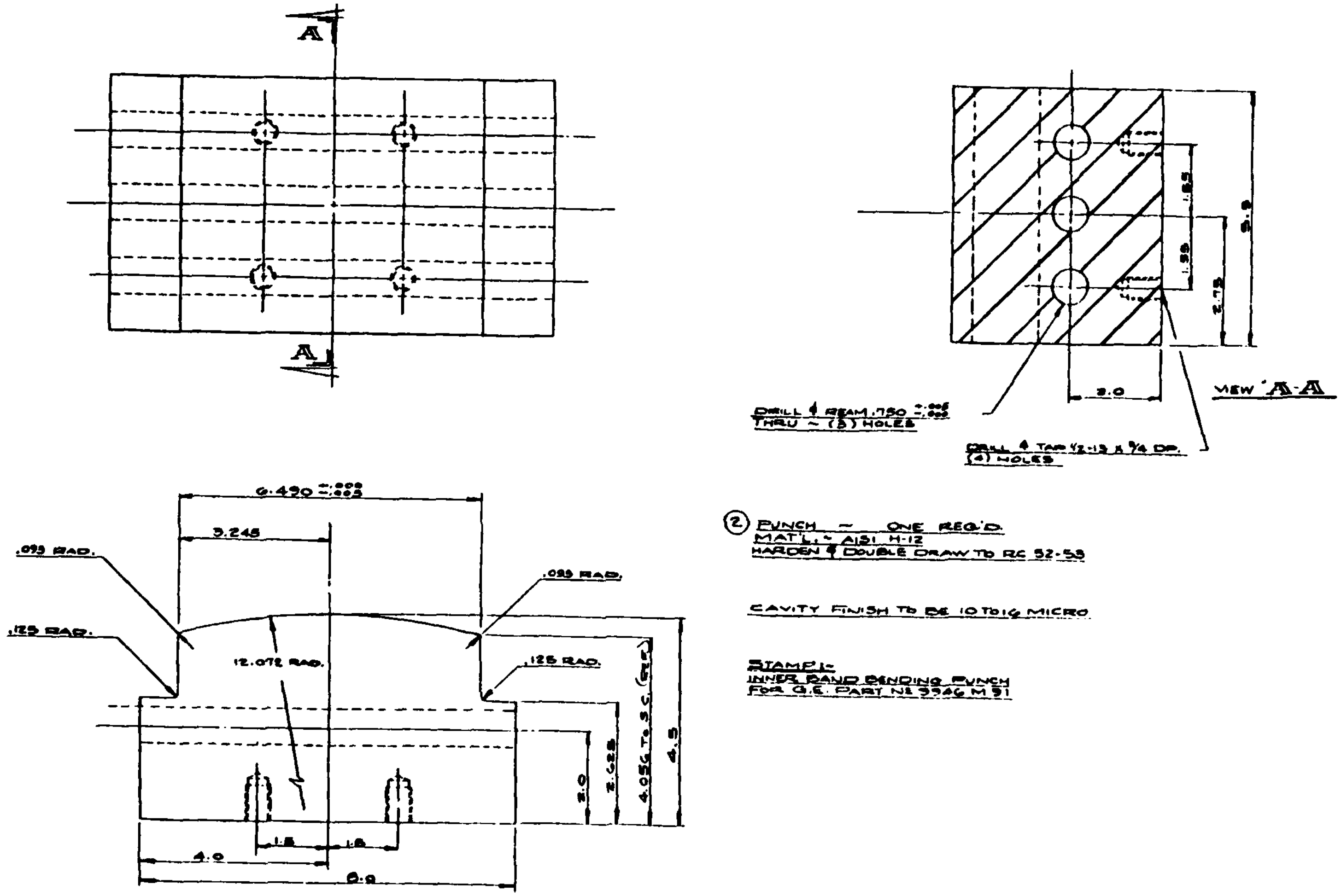


Figure 6. (Continued)

3.3.3 HPT Vane Tooling

Tooling for the HPT vane is considerably different than that required for the LPT vane and inner band because directional forging rather than forge bending is used.

Two sets of HPT vane directional forging dies were designed and built by TRW for use in the program. The first set of tooling was designed to produce a net shape vane. But the results of several forging trials indicated that some die design changes were required because complete die fill was not achieved and trailing edge texture was not maintained.

The second set of directional forging tooling shown in Figure 7 was designed to produce a near-net shape HPT vane. The near-net shape design incorporated a .030-inch envelope and a .25-inch extension on the trailing edge.

3.4 HPT PREFORM SELECTION

The technical plan for Phase I was originally designed for extruded airfoil shaped ODS NiCrAl alloy preforms to produce near-net shape HPT vanes. The possibility of achieving net shapes was investigated but later discarded as being not as cost-effective because of higher risks.

The YDNiCrAl alloy was supplied in an extruded kidney shape. The MA757 was supplied as an extruded plus flat rolled rectangular shape. The two HPT vane preform shapes and conversion methods to near-net vane shape is shown in Figure 8.

In the development of a YDNiCrAl preform process, five airfoil shaped extrusions were prepared in two extrusion studies. They all failed to produce acceptable microstructure for F101 HPT vane preform material. Two preforms for near-net and three for net shapes were extruded. Various recrystallization heat treatments were used but all produced either a fine grained structure or a high modulus crystallographic orientation in the nose region as shown in Figure 9.

Since the correct "cube on-edge" texture can more easily be produced in rectangular bar as shown in Figure 10, it was decided to obtain YDNiCrAl in rectangular bar form and machine near-net shape airfoil preforms in the same manner in which MA757 rectangular bar was machined. MA754 was also obtained in rectangular bar form. Rectangular starting shapes are a low risk and cost effective preform approach. The use of rectangular starting stock had the additional significant advantage of applicability to all ODS producers, whereas, the shaped preforms were available solely from Special Metals.

Although the HPT preform design is relatively simple, several iterations and modifications of design were evaluated to determine the best design to yield a product with an acceptable microstructure.

Three forging campaigns were performed during the course of the program, two in Phase I and one in Phase II. Sketches of the preform designs for the first campaign are shown in Figure 11.

Figure 7. NNS HPT Forging Die

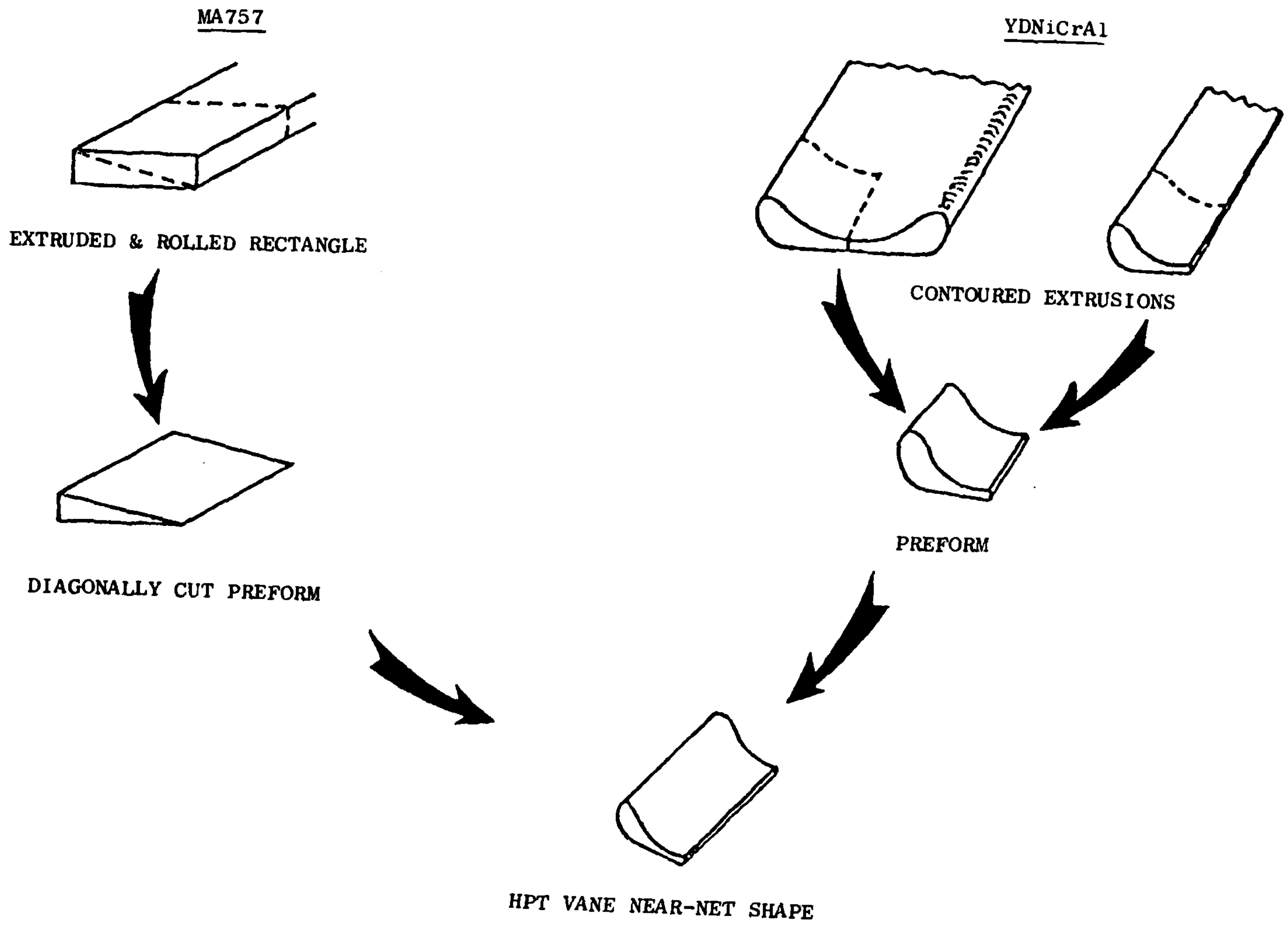


Figure 8. Original Phase I HPT Vane Near-Net Shape Process Concept

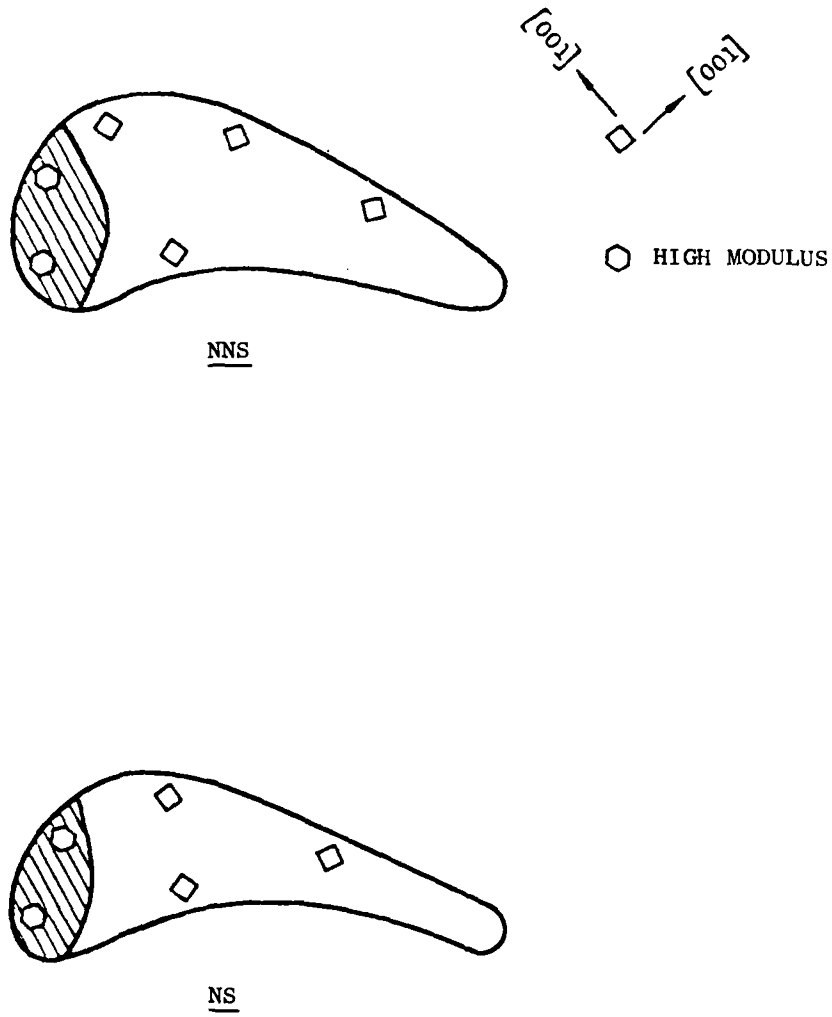


Figure 9. HPT Vane Extruded Airfoil Preform Textures

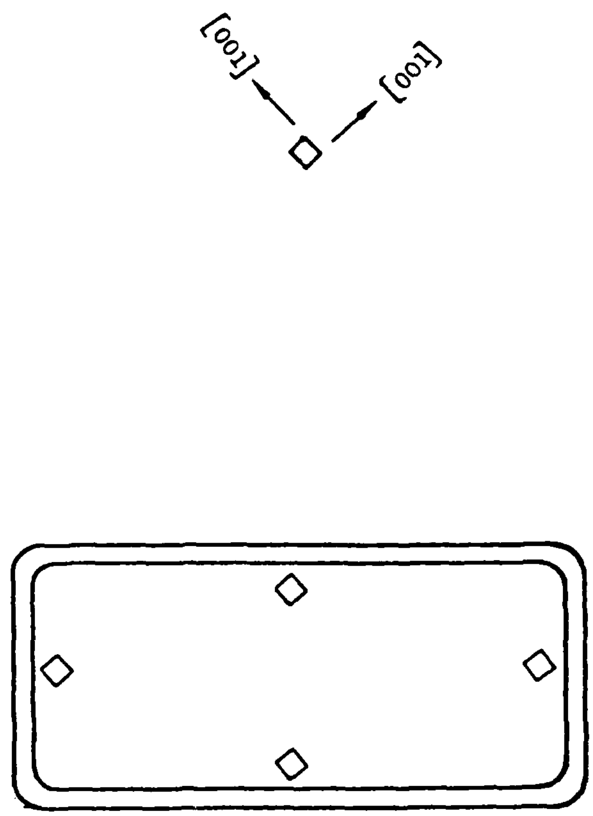
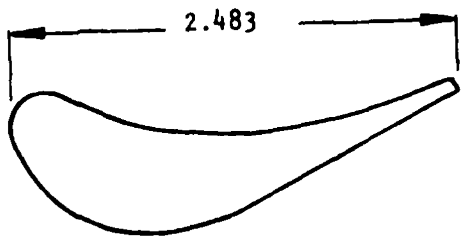
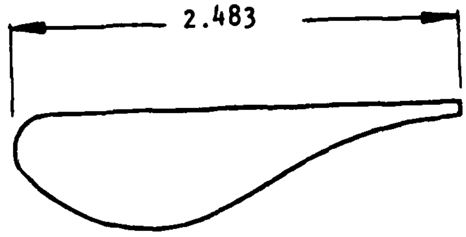


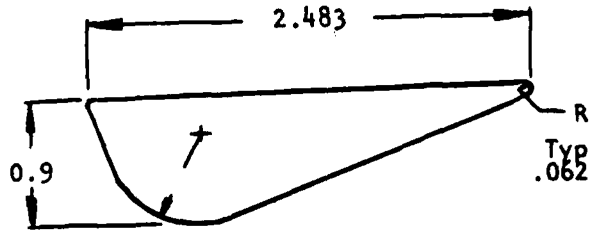
Figure 10. Extruded and Rolled Rectangular Bar Texture



A) AIRFOIL SHAPE



B) FLATTENED AIRFOIL SHAPE



C) TRIANGLE SHAPE

Figure 11. Phase I HPT Preforms 1st Forging Campaign

A second series of preform designs were prepared by TRW for the second forging campaign in Phase I. Five different wedge shaped preform designs, as shown in Figures 12A and 12B, which varied in pitch thickness, chord width and mass distribution, were investigated. Preform designs Nos. 1, 2, and 4 were similar, differing only slightly in pitch thickness and mass distribution. All three were the same chord width (2.483"). Preform design No. 3 differed only by an additional .080" on the chord width. The extra width allowed for width reduction by bending during forging to the vane curvature. The preform was actually wider than the die cavity and required bending during the stroke of the male die. Design No. 5 was simply the result of bisecting the rectangular MA754 bar on the diagonal. The chord width was the same as design Nos. 1, 2, and 4 but the pitch thickness and mass distribution were significantly different.

Phase II Preform Design

The preforms prepared for Phase I were all designed to be used in forging net shape HPT vanes. The Phase II preforms were designed to be used in forging near-net shape HPT vanes. Three preform designs were selected as shown in Figure 13. All three preform designs were wedge shaped. Design #1 allowed for removal of material by generating a radius between the trailing edge and the pitch. Removal of this material meant that the preform would be uniformly worked about 20% in this area and less for the remaining areas. Design #2 is similar to Design #1 except that now the material has not been removed between the trailing edge and the pitch and the material would be non-uniformly worked up to about 47% in this area. In design #3 the bar is simply cut on the diagonal. Reductions approaching 50% would occur during forging.

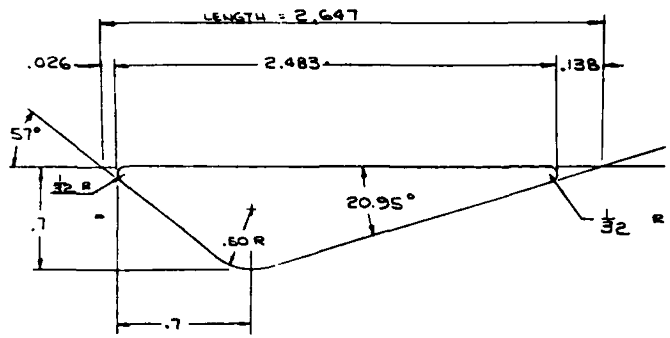
3.5 PHASE I DIRECTIONAL FORGING

The original objective of Phase I was to demonstrate that directional forging is a viable and economical process to produce net shape HPT vanes from ODS materials.

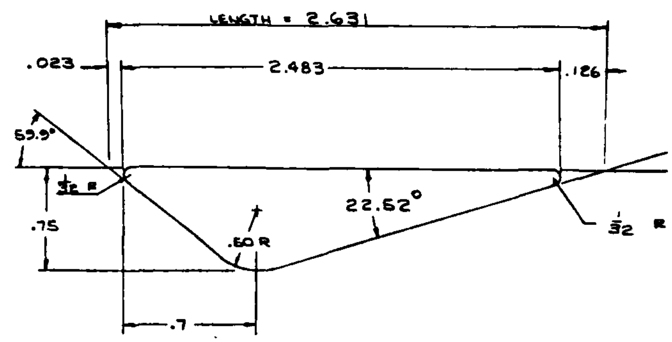
3.5.1 First Forging Campaign

Forging trials were conducted at TRW on a 1000 ton mechanical press, photo similar to the one used is shown in Figure 14. The die temperature was maintained at 400°F and the elapsed part transfer time from the furnace to the forging operation averaged 4 to 5 seconds.

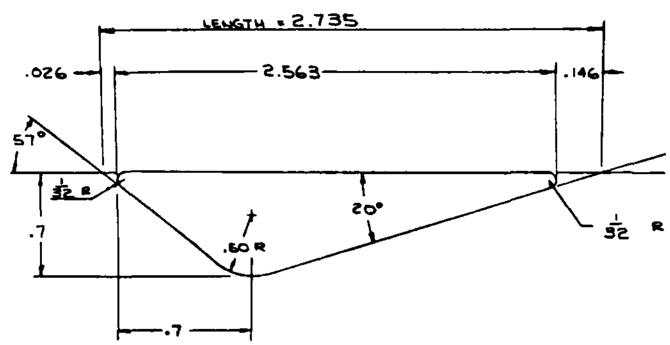
MA754, MA757 and YDNiCrAl preform shapes as previously illustrated in Figure 11 were forged to F101 HPT vane configuration. The forging condition and results are listed in Table 2. The MA754, MA757 and YDNiCrAl "wedge" (Figure 11C), "flattened-airfoil" (Figure 10B) and "airfoil" (Figure 11A) shaped preforms prepared from as-rolled (unrecrystallized) rectangular bar were forged unclad at 1950°F and 2050°F. All preforms were frit coated which provided lubrication and effectively reduced the heat loss from the preform to the cooler (400°F) tooling.



a. DESIGN #1

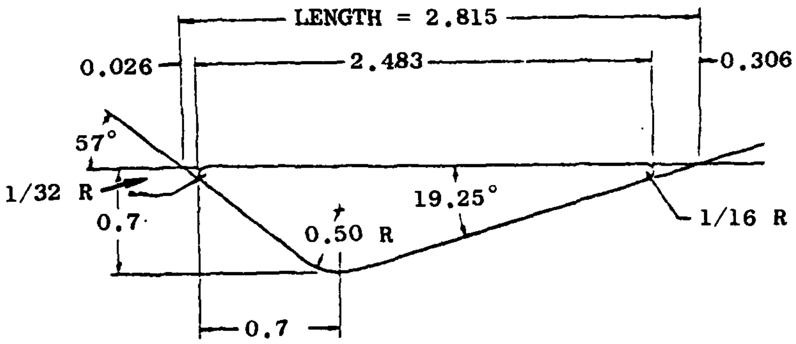


b. DESIGN #2

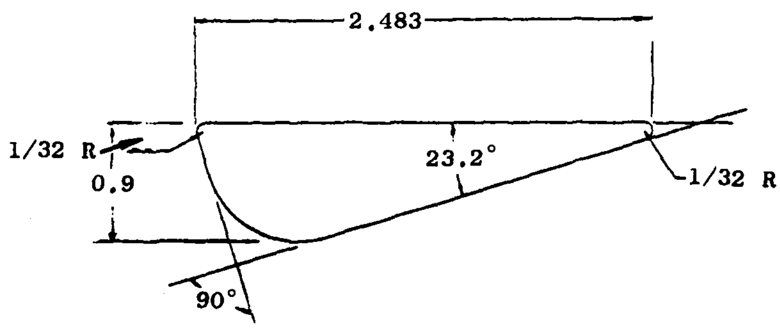


c. DESIGN #3

Figure 12A. Phase I, Forging Campaign II HPT Vane Preform Designs



d. DESIGN #4



e. DESIGN #5

Figure 12B. Phase I Forging Campaign II HPT Vane Preform Designs (cont'd)

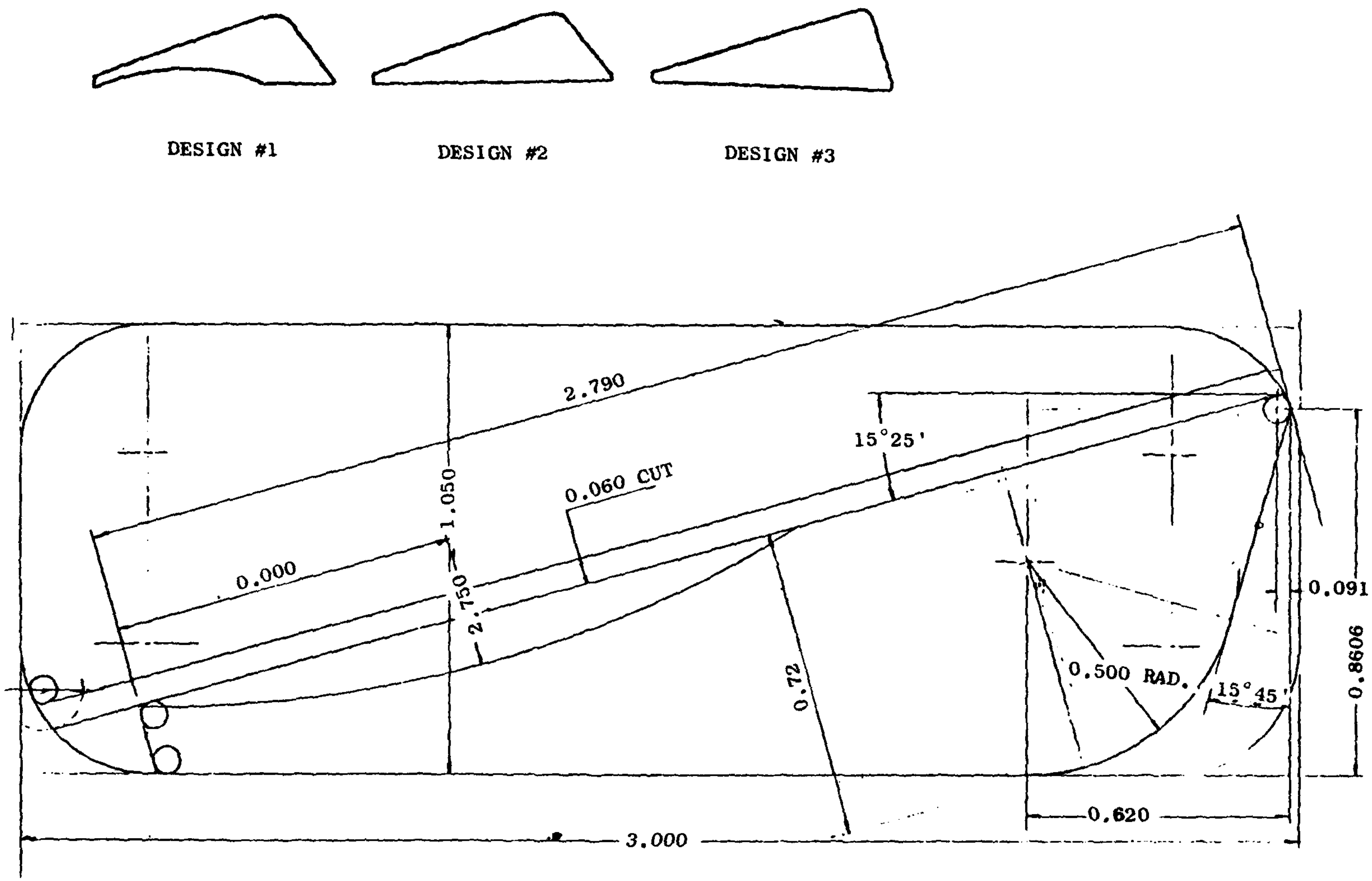


Figure 13. Preform Designs for HPT Vane Phase II Forging Campaign

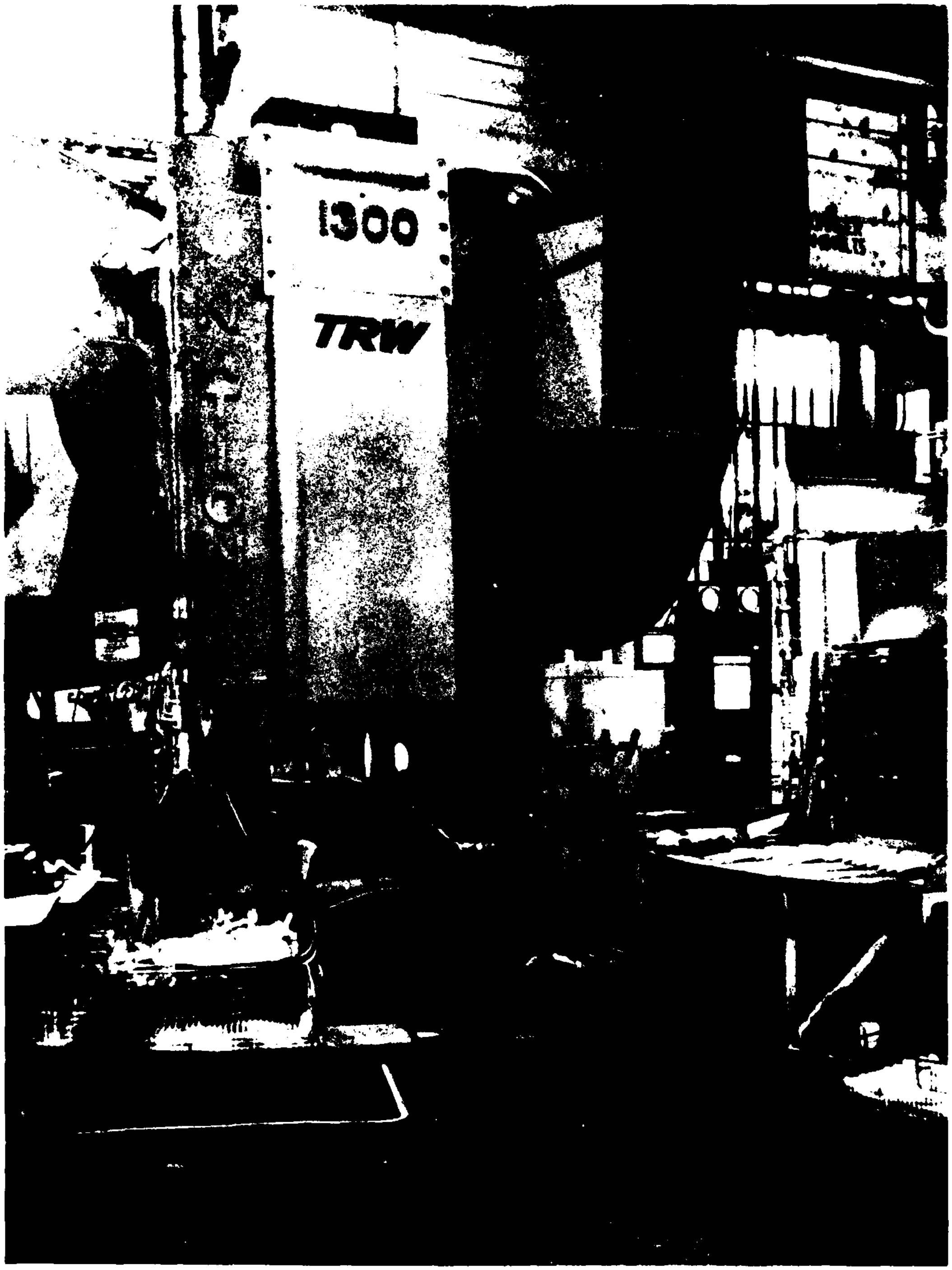


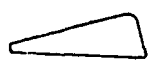
Figure 14. Forge Press Similar to One Used for Directional Forging

TABLE 2

TASK I CAMPAIGN I FORGING TRIALS

Sample Number	Material	Microstructural Condition	Preform Shape	Forge Temperature	Microstructure (1)
16	MA 754	As-Rolled	Wedge (2)	1950°F	Good
10	MA 754	As-Rolled	Wedge	2050°F	Good
8	MA 754	As-Rolled	Flattened Airfoil (3)	2050°F	Good
5	MA 754	As-Rolled	Airfoil (4)	2050°F	Good
13	MA 757	As-Rolled	Flattened Airfoil	1950°F	Good
11	MA 757	As-Rolled	Airfoil	1950°F	Good
6	MA 757	As-Rolled	Flattened Airfoil	2050°F	Good
1	MA 757	As-Rolled	Airfoil	2050°F	Good
2	MA 757	Rx'd	Airfoil	2050°F	Good
15	YD NiCrAl	As-Rolled	Wedge	1950°F	Non 100
14	YD NiCrAl	As-Rolled	Flattened Airfoil	1950°F	Good
12	YD NiCrAl	As-Rolled	Airfoil	1950°F	Good
9	YD NiCrAl	As-Rolled	Wedge	2050°F	Non 100
7	YD NiCrAl	As-Rolled	Flattened Airfoil	2050°F	Good
3	YD NiCrAl	As-Rolled	Airfoil	2050°F	Good
4	YD NiCrAl	Rx'd	Airfoil	2050°F	Good

(1) After 2400°F recrystallization heat treatment

(2) 

(3) 

(4) 

3.5.2 Second Forging Campaign

The second forging campaign was conducted using only MA754 wedge shaped preforms. All material was supplied in the hot-rolled condition. All forging was conducted similar to the processing discussed for the first forging campaign, that is, the same forging press, forge tooling, heating cycle and lube practices were employed. The forging schedule is shown in Table 3. All forging was conducted between 1750° and 1950°F. Preforms used are those shown in Figure 12. Besides the evaluation of forging temperature and preform design, two glass coatings were also evaluated as indicated in Table 3. A total of twenty forgings were produced.

3.6 PHASE II HPT DIRECTIONAL VANE FORGING

Phase II has established near-net-shape forge bending processes for LPT vanes and HPT bands, and demonstrated the reproducibility of the HPT vane directional forging process established in Phase I. Isothermal shape rolling was also investigated in this phase of the program on HPT vane stock.

HPT Vane Forging

Forty wedge shaped preforms of three designs were prepared from asrolled (unrecrystallized) MA754 bar and forged as indicated in Table 4. A photo of the preforms is shown in Figure 15. The forged NNS design was the F101 HPT vane configuration with a .040" envelope and a .25" extension on the trailing edge as shown in Figure 16. Two preforms of each configuration were obtained from the 1.05" thick X 3.0" wide rectangular forging process. Two vanes can be produced from the same quantity of material as is now required to conventionally machine one vane. Design No. 3 was prepared by simply cutting the rectangular shaped bar on the diagonal and radiusing the corners. This design is the least expensive to prepare although it promotes higher forging reductions (40%-50%). Design No. 2 was prepared the same way as Design No. 3 but some material was machined away in the region forward of the pitch thickness. This design reduces the forge reduction in the forward section of the vane but has about a 45% reduction between the pitch thickness and trailing edge. Preform Design No. 1 was prepared by machining away some material forward of the pitch thickness and some between the pitch thickness and trailing edge on the concave side of the preform. This reduces the vane NNS forging reduction to a fairly uniform 20%.

TABLE 3

PHASE I - CAMPAIGN II HPT VANE FORGING SCHEDULE

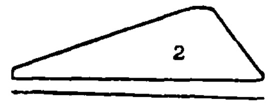
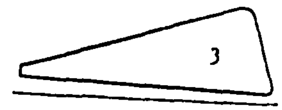
S/N	Preform Design (a)	Forging Temperature (°F)	Glass Coating
1	1	1950	A
2	1	1950	B
3	2	1950	A
4	2	1950	B
5	3	1950	A
6	3	1950	B
7	4	1950	A
8	4	1950	B
9	5	1950	A
10	5	1950	B
11	1	1850	B
12	2	1850	B
13	3	1850	B
14	4	1850	B
15	5	1850	B
16	1	1750	A
17	2	1750	A
18	3	1750	A
19	4	1750	A
20	5	1750	A

(a) Refer to Figure 12.

A - Alkali Alumina Borosilicate
B - Leaded Sodium Alumina Borosilicate

TABLE 4

MA754 NNS VANE FORGE PROCESSING - PHASE II

Material	Process Temp., °F	Preform Design/Number Forged		
		 1	 2	 3
Heat No. 0104A2B2-1	1750	9		
	1800	9	6	6
Heat No. DT0076B1-2	1750	1		
	1800	1	4	4

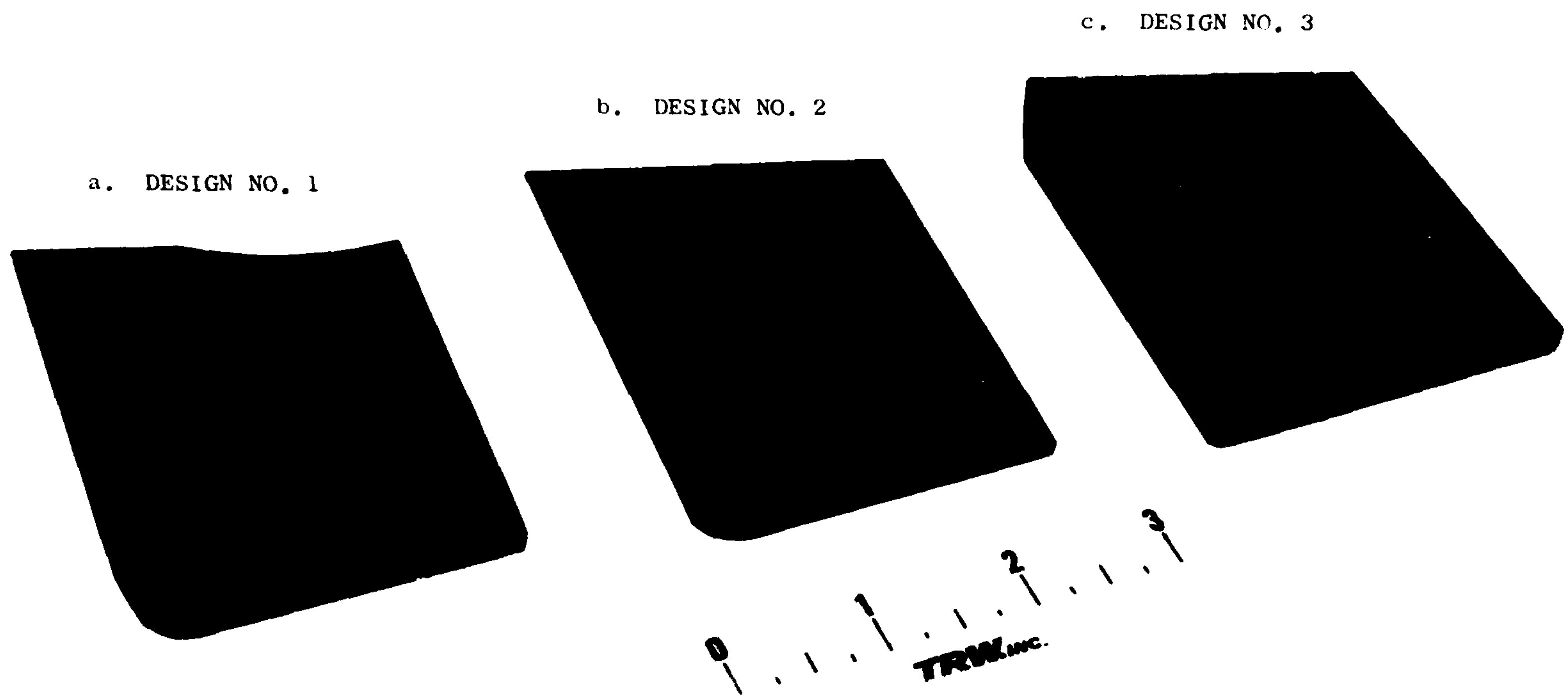


Figure 15. Finish Machined MA751 Preforms Prior to Coating and Forging

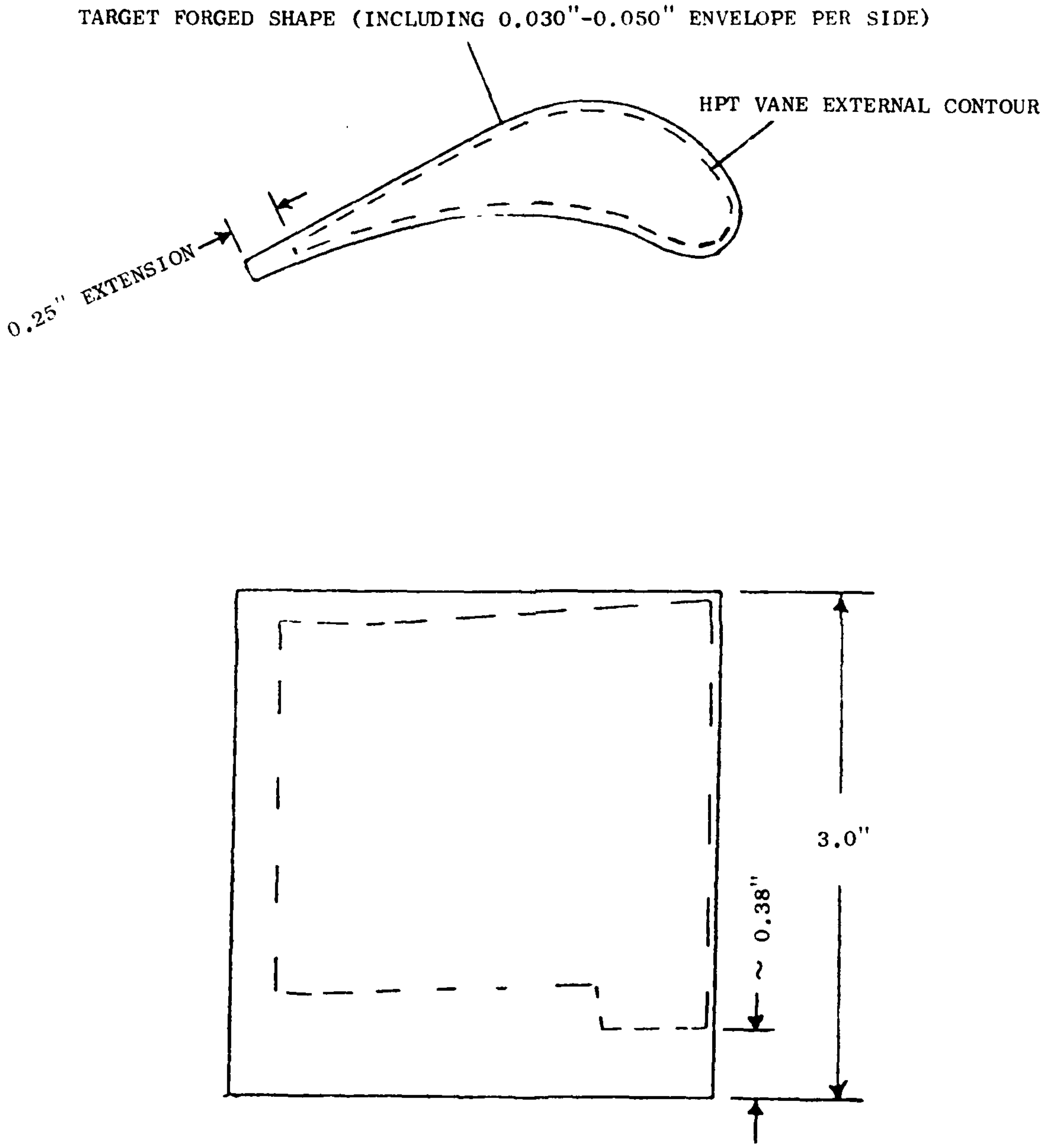


Figure 16. F101 HPT Vane and NNS Configurations

3.7 ISOTHERMAL SHAPE ROLLING

In isothermal shape rolling (ISR), the work piece is resistance heated by passing electrical current between the shaped work rolls and through the work piece. See Figure 17.

Three attractive features were offered by the ISR technique.

(1) Heating tends to be uniform even with variable cross sections since resistance heating is directly proportional to the section thickness.

(2) Long sections can be worked, thereby eliminating end waste.

(3) Net shapes have been achieved by close control of working reductions.

Material: Unrecrystallized MA754 was used for the ISR evaluation.

Tooling: The composite roll set for rolling vane stock shown in Figure 18 was used for the ISR evaluation. Each roll consisted of an outer ring of a circumferentially forged MT104 molybdenum alloy "tire" supported on a core of pressed and sintered molybdenum. The tire and core were assembled by shrink fitting together and vacuum brazing at 2300°F using a cobalt/palladium braze alloy to fill in between the "teeth" on the PS molybdenum core. The brazed roll set was finish machined to cylindrical configuration, installed in the ISR machine and evaluated using two inch wide feed stock. This setup is demonstrated in Figure 19.

Four drag-probes, shown in Figure 19 were used to measure voltage drops from core to tire in each roll and between the two tires through the feed stock. Temperature uniformity was maintained across the width of the two inch feed stock.

As part of the tooling package a feed stock guidance system was used consisting of a feeder unit on the impact side of the rolls and a tension take-up unit on the output side. The feeder unit was designed to force feed up to 36 inch lengths of material with cross sections up to 2.5 inch wide and 1 inch thick under axial compressive loads up to 15000 pounds. The take up unit was designed to help maintain alignment by applying tension loads to the rolled vane stock.

Preform Shape

Four unrecrystallized MA754 rectangular bars 36 inches long were utilized. The material preforms were prepared by saw cutting each bar diagonally into two triangular section bars. Sawing was performed with a DoAll Bandsaw Model 3612-3 with a hydraulic feed table. The sawing conditions were as follows:

- DoAll Imperial Bi-Metal Saw Blade, 174 inches long by 1 inch wide with 6 teeth per inch.
- Blade speed: 50 SFM

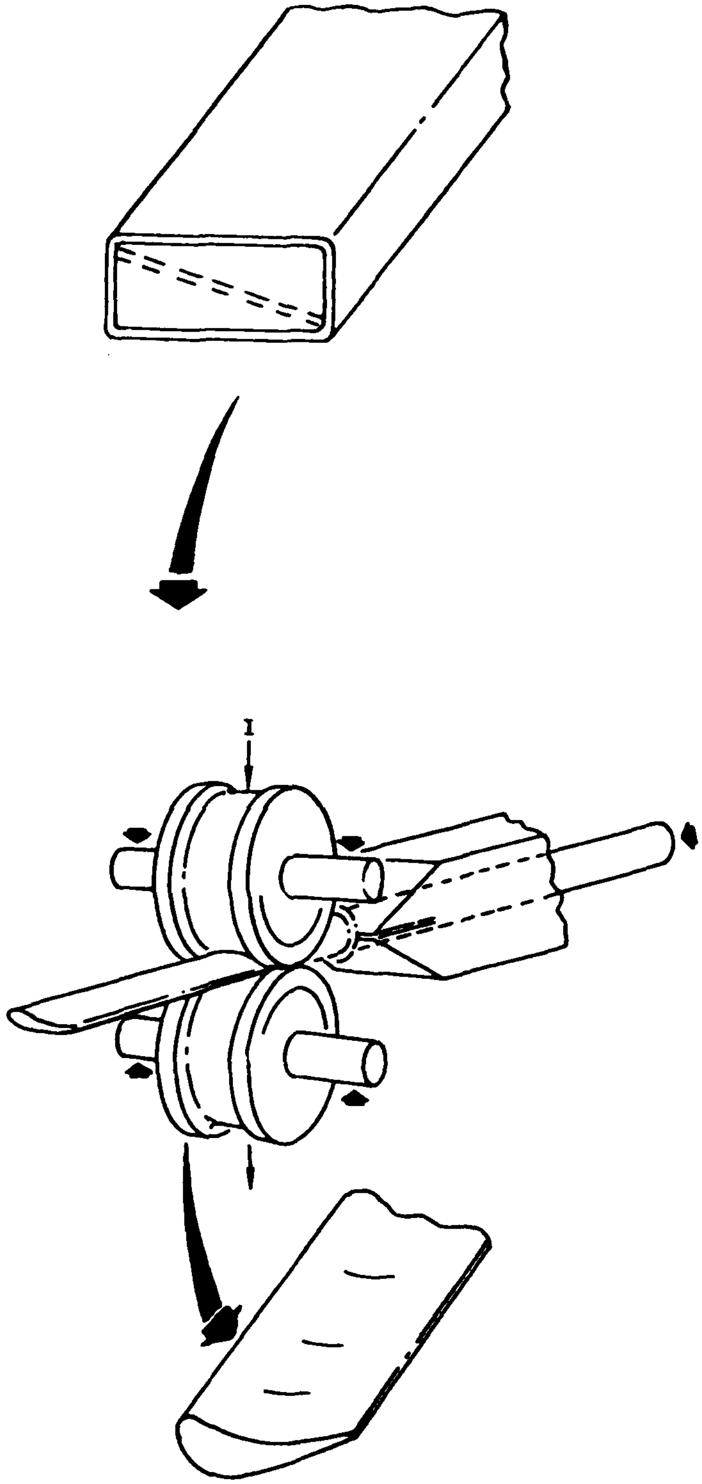


Figure 17. Solar ISR ODS Alloy HPT Vane Process

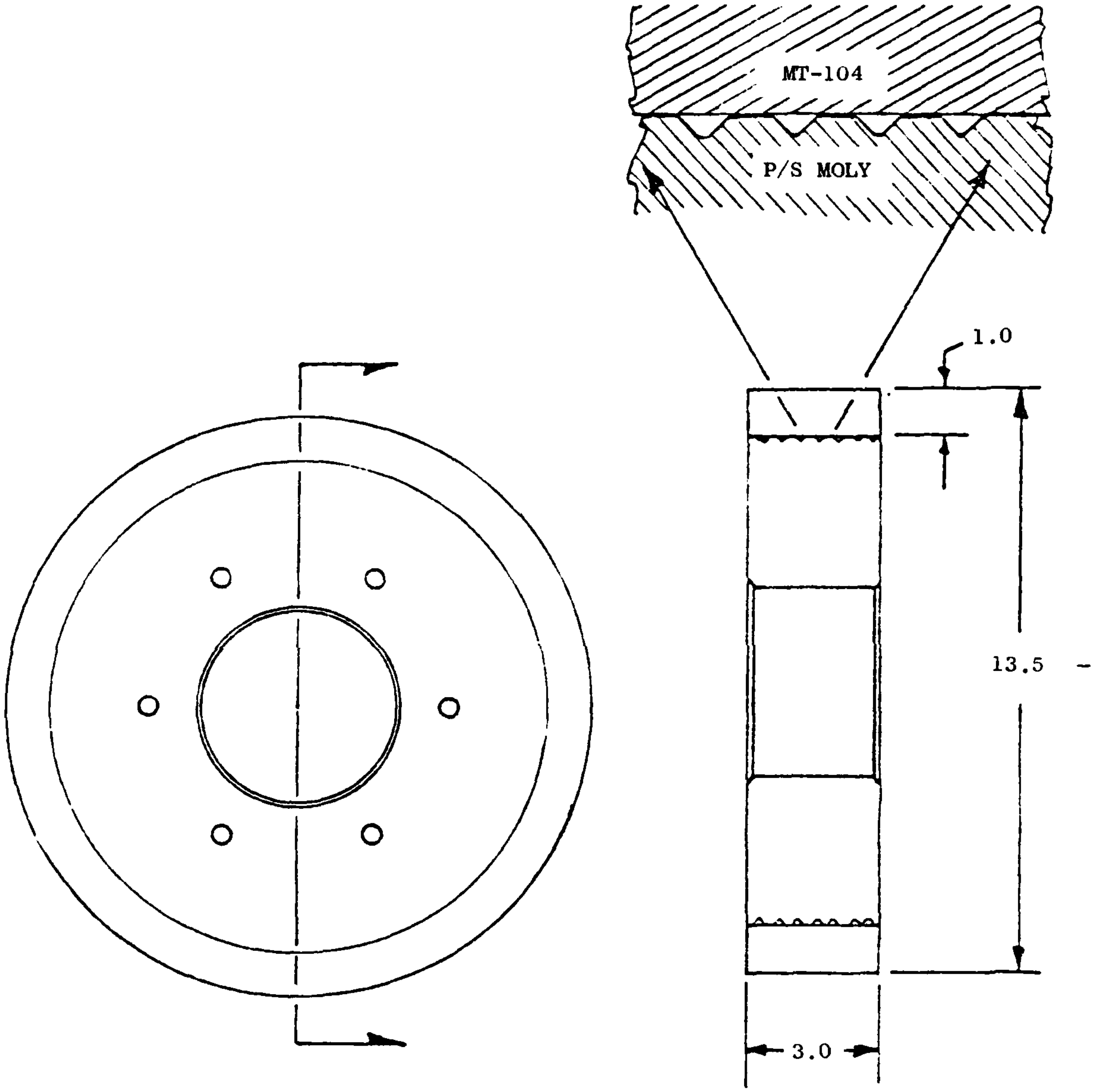


Figure 18. Basic Design of ODS Vanestock Roll Set

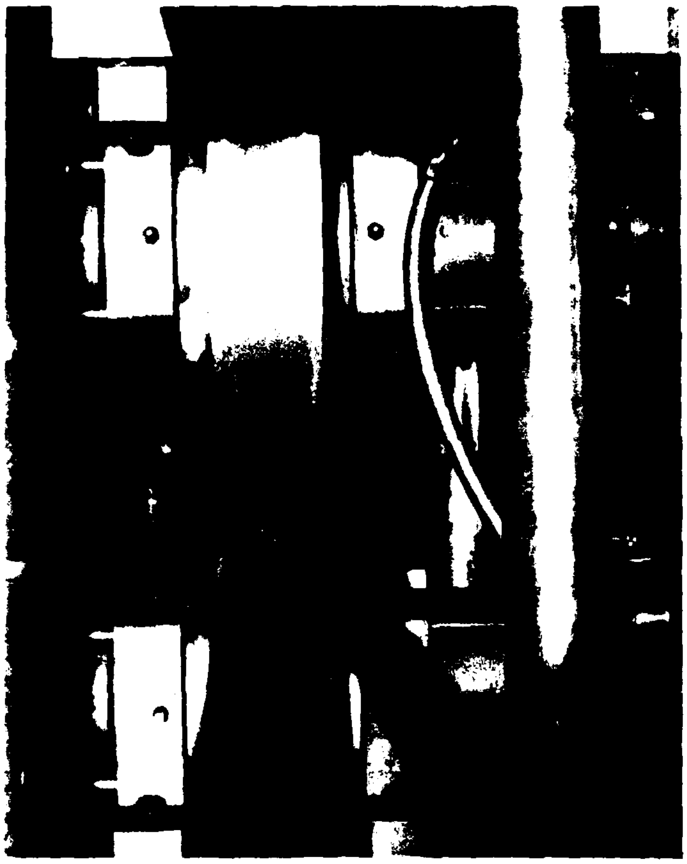


Figure 19. Strip Rolling With 3 In. Roll Set as Viewed From Inlet Side of Rolling Mill (#78-3393)

- Table feed force: 43 pounds (35 psi on 1.25 in. diameter cylinder)
- Cutting speed 6 inches per hour.

An initially new blade remained in excellent condition after sawing of the four ODS alloy bars (approximately 130 inches of cutting). The sawing operation required no operator assistance other than fixture repositioning necessitated by the 12-inch stroke limit of the feed table.

The steel cladding was removed in 25% nitric acid water solution. Additional machining was required to reduce the chord width from 3.0 inches to 2.5 inches and to achieve better initial electrical contact between the rolls and work piece.

Isothermal Shape Rolling

The first ISR trials resulted in material reductions of approximately 10%. Although there was adequate power to heat the 2.5-inch wide preform, the squeeze capacity was not adequate to achieve the required reductions. The squeeze force problem became evident as the area of the "footprint" (contact area) increased with increasing reduction, demanding more squeeze to operate on the larger area. The "bite" must be reduced to keep the footprint area within the capacity of the machine. As soon as rolling of preforms was begun, the problem of inadequate bite became severe. A small bite may mean no contact (and, hence, no heating) over part of the preform.

The ISR was conducted in 10 sessions. Table 5-A illustrates preform identification and rolling parameters. Table 5-B lists corrective actions for the each rolling session. Some of the principal problems occurring in sessions 1 & 2 were the instability of the shape in the rolls, skewing and rotation. In session 3 excessive bending and trailing edge cracking were observed. The cracking problem was resolved by removing the tension unit from the output side of the ISR equipment.

Complete roll cavity fill was improved by further preform machining to nearer-net shape. Additional preform machining was required because the maximum achievable reduction was only 10% as compared to the 30% required for uniform heating and reduction. Contour machining is not expected to be required with a full capacity machine.

The overall surface condition of the isothermally rolled material was comparable to that of the NNS forged vane material. However, after ten rolling trials the molybdenum tooling used for the ISR process showed signs of distress. Surface impressions, nicks and dents were observed. The moly tooling was not as durable as the steel tooling used for directional forging. The level of machining required to achieve an acceptable surface condition on ISR vane material would be approximately the same as for directionally forged material until surface defects are encountered from the tooling. This could result in the ISR vane being machined undersize in order to clean up.

TABLE 5 - PART A

ISOTHERMAL SHAPE ROLLING OF UNCRYSTALLIZED MA754 ODS ALLOY VANE STOCK

ESTABLISHMENT OF ROLLING PARAMETERS

	ODS Alloy Feedstock		Rolling Parameters					
Rolling Session	Bar No. /Pass	Preform Configuration	Roll Separation Force (lb)	LE Temp (°F)	Current (kiloamps)	Speed (ipm)	Feed Force (lb)	Front Tension (lb)
1	1st half A1		21,600	1850	27.5	2.02	8,300	610
2	2nd half A1		24,000	1950	32.5	2.02	8,300	2050
3	1st half A2		24,000	2050	19.6	2.02	8,300	2050
4	2nd half A2		21,600	1970	33.0	2.02	5,000	1360
5	B2		19,200	1930	32.6	2.02	5,000	2050
6	1st half C1		33,600	N/A	33.1	2.02	5,000	2050
7	2nd half C1		33,600	N/A	32.7	2.02	11,600	1700
8	C2		43,200	1810	33.0	1.62	13,300	2730
9	C2/2nd pass		33,600	1970	29.3	?.60	Not Used	2730
10	B2/2nd pass		43,200	N/A	31/5	2.43	3,200	2050

TABLE 5 - PART B

ISOTHERMAL SHAPE ROLLING OF MA 754 ODS ALLOY VANE STOCK

ESTABLISHMENT OF ROLLING PARAMETERS

Rolling Session	t_{max} (in.) Initial	Final	Results: Observations	Corrective Action for Subsequent Rolling Session
1	0.847-0.872	0.649-0.670	No cracks; LE not filled; skewed to LE	• Added hydraulic front tension • Closed die gap by 0.090 in.
2	0.877-0.890	0.625-0.629	Skewing eliminated; improved thickness control; TE overfill; cracks at TE; LE not filled	Rotated feedstock placing face t parallel to roll axes
3	0.800-0.843	N/A	LE fully formed; TE fractured due to bending in roll bite	Rotational constraints removed from feedstock
4	0.855-0.875	N/A	No cracking of TE; LE not filled; excessive reduction at TE	Feedstock machined: 0.75 in. radius on apex opposite c, c machined to reduce metal near TE; apply twist gage
5	0.866-0.786	0.614-0.598	Improved but still incomplete fill of LE; flash reduced at TE; twist of vane at roll exit shown to be feasible	Increase roll separation force to maintain roll platens against mechanical stops
6	0.764-0.753	0.595-0.594	Excellent thickness control over 5 in. rolled segment; LE still not filled	Increase feed force to promote lateral flow
7	0.757-0.736	0.594-0.572	LE still not filled	Reduce rolling speed and increase feed force
8	0.695-0.725	0.581-0.590	Chord 2.320 to 2.370 in.; flash formation at TE; LE not filled	Increase rolling speed for second pass
9	0.581-0.590	0.548-0.557	Manual twist at roll exit produced 16° twist/ft. LE nearly filled	Provide minimal feed force to overcome friction of inlet nozzle
10	0.614-0.598	0.566-0.548	Chord 2.463 to 2/469 over 20 in. rolled length; LE nearly filled no defects indicated by penetrant test	Higher force and higher current needed for complete success. This will require larger (production) machine.

More uniform heating and metal flow were obtained in rolling sessions 5 to 10. Sessions 5 through 8 gave an airfoil maximum thickness of 0.57 to 0.59 inch. The leading edge was difficult to fill because homogeneous flow throughout the thickness of a heavy section could not be achieved with light passes that work the surface. Material rolled in session 10 almost completely filled the roll cavity with 0.006 inch variation of chord and 0.004 inch variation of airfoil maximum thickness along a 30-inch length. The piece rolled in this session is shown in Figure 20.

Recrystallization Response

The ISR sections were sent to General Electric for heat treatment and evaluation. Sections were removed from ISR preforms exhibiting the most uniform temperature distribution and reduction and heat treated in a fast heatup 2400°F/1 Hr/air cool. As shown in the top view of Figure 21, the net shape preforms contained a very large misoriented grain structure. Additional material was removed from the same bar and heated at a slower rate to 2400°F. Material was stabilized at 2000°F then heated to 2400°F in 2 Hrs. held for 1 Hr. and air cooled. The lower photo in Figure 21 indicates that the microstructure was considerably improved but the mistexture was not completely eliminated. The phenomena of large grain recrystallization and mistexture in rapid heatup indicates that the actual rolling temperatures were higher than intended and probably in the range of 2000°F.

Based on the incapacity of the ISR machine to effectively roll HPT vane shapes and the unexpected recrystallization responses, further evaluation of these shapes was halted.

The overall conclusion of the ISR effort is that the process still has potential for near-net or net ODS shapes but that present machine capacity is insufficient to roll widths necessary for the HPT vane. In addition precise temperature control within the narrow ranges necessary to preserve recrystallization microstructures in ODS alloys could be a problem. Direct measurement of actual interior metal temperatures is not possible, forcing reliance on surface temperatures only.

3.8 LPT VANE AND HPT BAND PLATE PREFORMS

Plate rolling parameters were established for the HPT band and LPT vane preform material. The material was rolled at General Electric on a Waterbury Farrel 10" X 10" rolling mill. Sections of the asreceived MA754 bar (unrecrystallized with steel clad intact) were rolled at temperatures of 1500°F, 1600°F, 1700°F and 1800°F. The results are shown in Table 6. The 1600°F rolling temperature produced recrystallization response comparable to standard MA754 bar material.

LPT Vane Preform Design

The LPT vane preforms were cut from hot rolled MA754 plate. The plate dimensions were 0.3-inches thick by 2.20-inches wide by 3.8-inches long. A sketch of the plate preform and the formed target shape are shown in Figure 22. The plate preform width allowed for positive location of the preform in the die and a 0.05-inch envelope for finish machining.

Figure 20. Isothermal Shape Rolled Section B2

FAST HEATUP RATE

SLOW HEATUP RATE

Figure 21. ISR Macrostructure

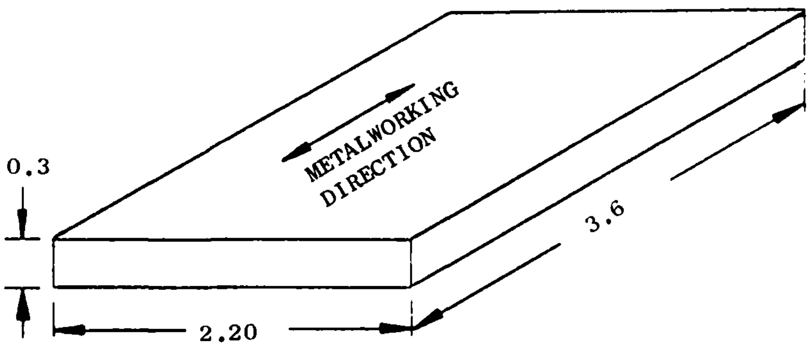
TABLE 6

MA754 PLATE ROLLING PROCESS ESTABLISHMENT (1)

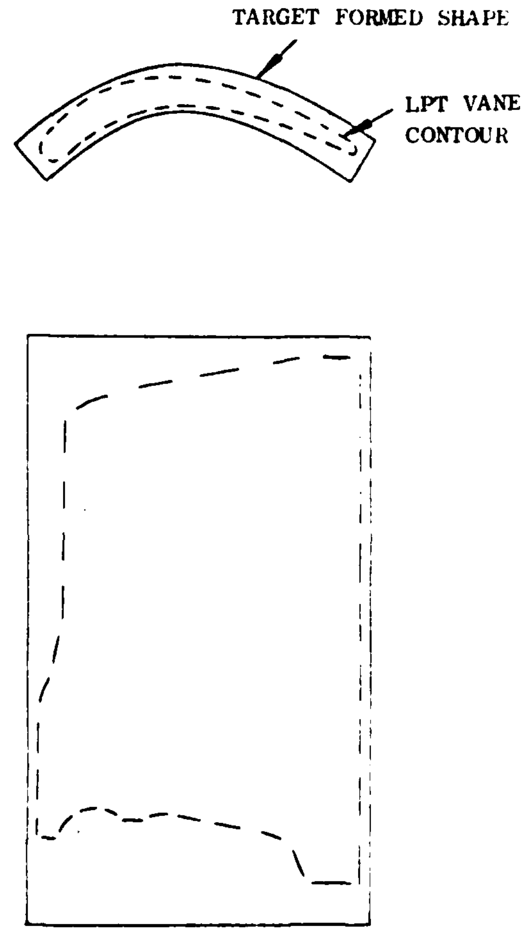
Material	Rolling Temperature	Integrity	Macrostructure (2)
DTO4A2B2-1	As-Received	Excellent	Normal, .010" x 20 L/d grains
"	1500°F	"	Small grain loss of texture
"	1600°F	"	Comparable to as-received
"	1700°F	"	Coarse grained (2x)
"	1800°F	"	Coarse grained (5x)

(1) Rolling Procedure: Starting material - 1.05" x 3.00" x 3.00" unrecrystallized, clad intact.
10% reduction and reheated each pass.
Rolled to 0.30" thickness.

(2) Subsequent recrystallization heat treatment (2400°F - 1 hour).



a. LPT VANE PREFORM



b. NEAR NET LPT VANE

Figure 22. LPT Vane Preform and Target Formed Near-Net Shape

Turbine Nozzle Band Preform Design

The turbine nozzle inner band preforms were cut from hot rolled MA754 plate. The plate dimensions were 0.7-inch thick by 2.98-inches wide by a minimum 5.5-inches and a maximum 6.5-inches length. A sketch of the plate preform and the formed target shape are shown in Figure 23. The plate preform allowed for a minimum 0.05-inch envelope on thickness and a 0.1-inch envelope on the sides. Ideally, a length of about 5.5-inches should be used for maximum material utilization for the inner band; however, since the plate material supplied was not in even multiples of 5.5-inches (plus material lost in producing the cut) the material was cut to obtain the maximum number of preforms from the plate between a length of 5.5 and 6.5-inches.

3.9 LPT VANE FORGE BENDING

LPT vane preforms were prepared by hot rolling as previously described. Only material rolled at 1650°F and 1850°F was used to make vanes with the majority from 1650°F material. Tab e 7 illustrates the vane forming schedule.

Plate forming trials were conducted with the tooling setup shown in Figure 24. The press utilized for the forming was a 50-ton hydraulic press. The dies were electrically heated to 400°F using cartridge heaters in the die blocks. Twenty LPT vane near-net shapes were prepared. The unrecrystallized rolled plate was glass coated, heated to 2050°F and forge/bent to the LPT vane curvature and twist as demonstrated in Figure 22.

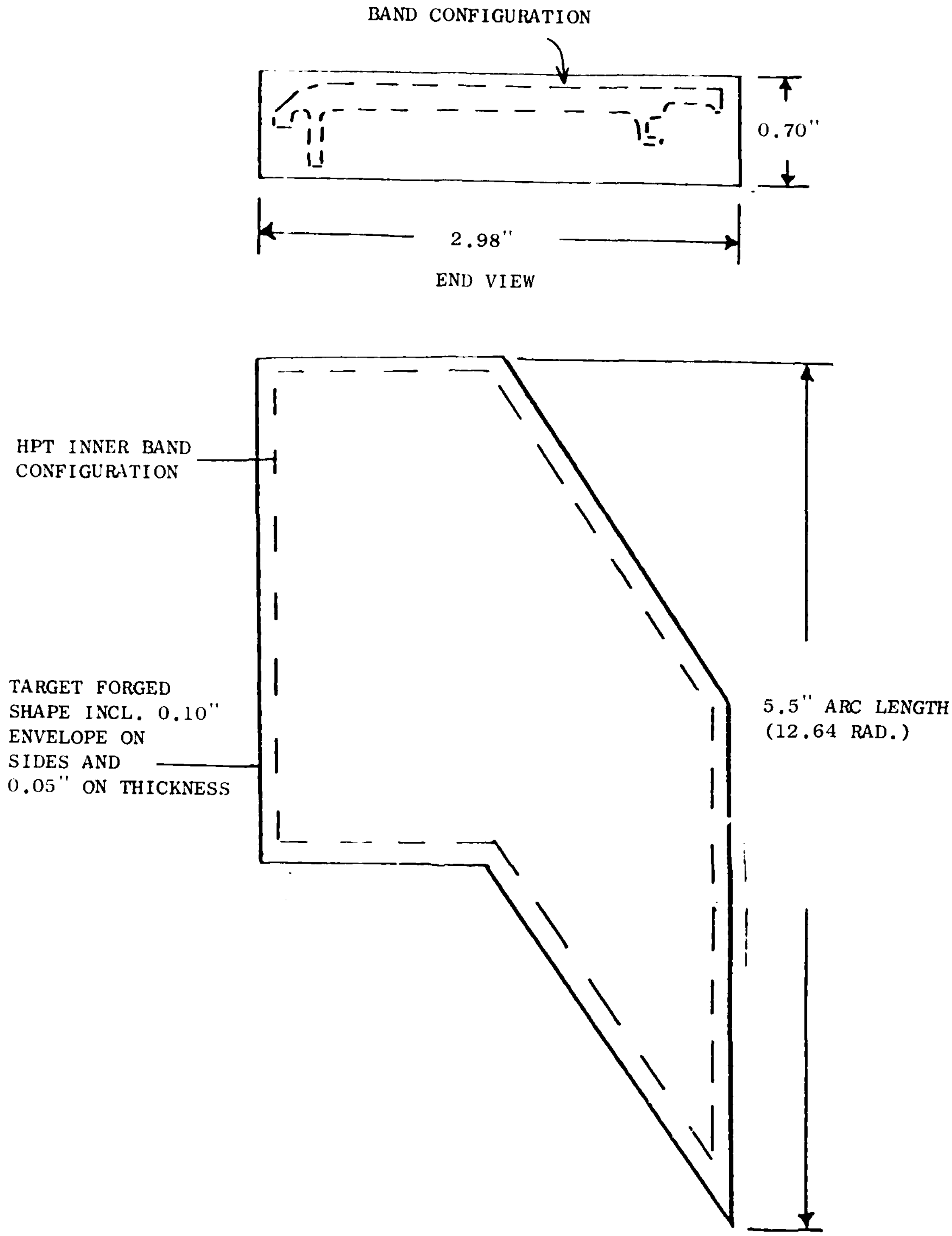


Figure 23. F101 HPT Band and NNS Configuration

TABLE 7

LPT VANE FORMING SCHEDULE

S/N (a)	Glass Coated
1	Yes
2	Yes
3	Yes
4	Yes
5	Yes
6	Yes
7	Yes
8	Yes
9	Yes
10	Yes
11	Yes
12	Yes
13	Yes
14	Yes
15	Yes
16	Yes
17	No
18	No
19	No
20	Yes
21	Yes
22	Yes

(a) S/N 1-19 Rolled at 1650°F.
S/N 20 Rolled at 1700°F.
S/N 21-22 Rolled at 1800°F.

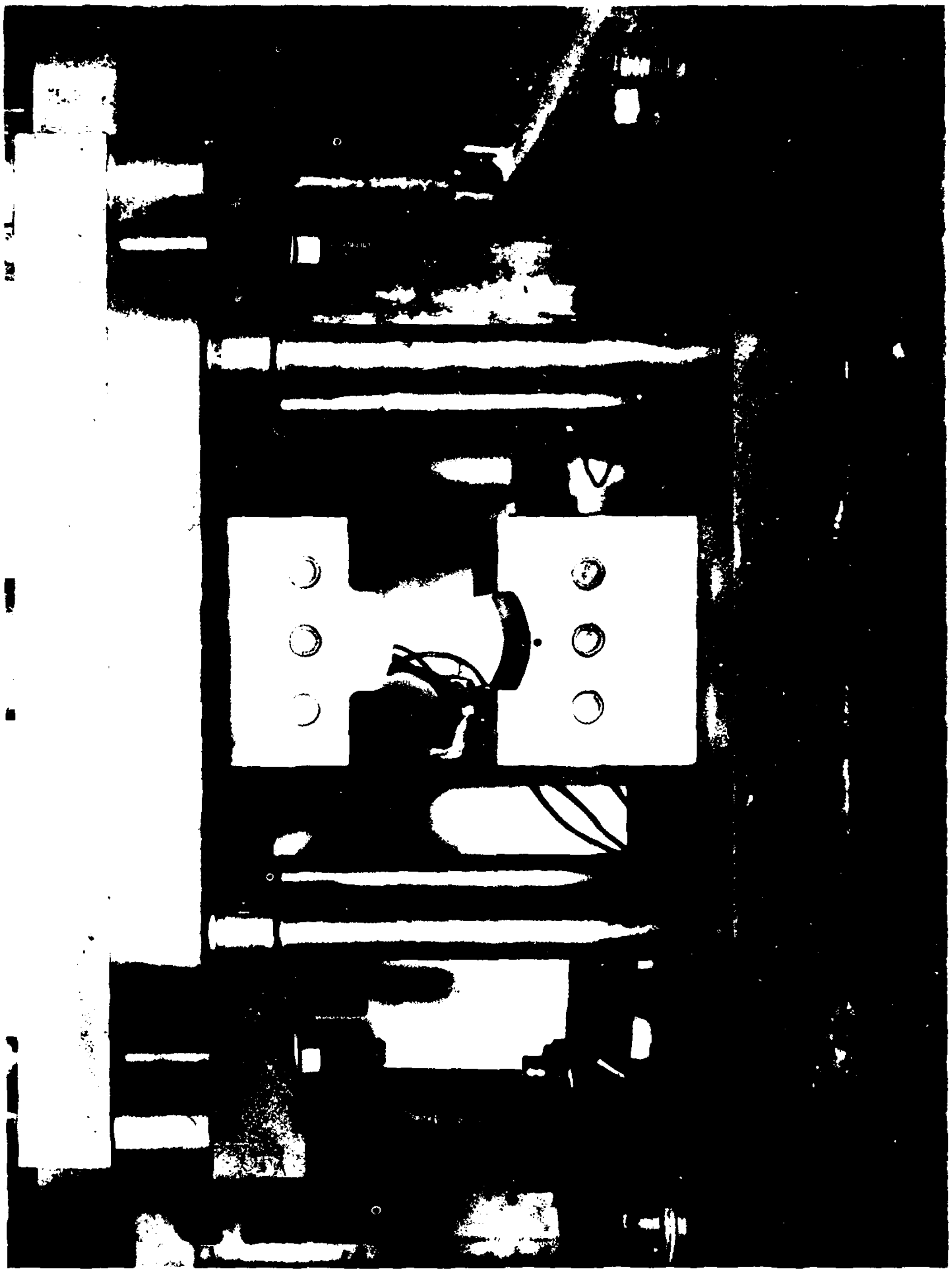


Figure 21. NNS Plate Forming Setup

3.10 HPT BAND FORGE BENDING

Preform material for the HPT bands was hot rolled at 1650°F to the required thickness. All HPT band preforms were prepared from unrecrystallized MA754 material.

Plate forming trials were conducted with a setup similar to the one shown for the LPT vanes in Figure 24. Preforms used were those shown in Figure 23. All process conditions were identical to those used for the LPT vanes except that the preforms were heated for twenty minutes. All preforms were sprayed with a leaded sodium aluminum borosilicate coating. The bending load applied was preset to about fifty tons which is equivalent to slightly less than six tons per square inch. A total of eighteen preforms were formed.

SECTION IV

NNS COMPONENT EVALUATION

4.1 HPT VANE EVALUATION

4.1.1 First HPT Vane Forging Campaign Results

The first forging campaign was conducted according to the schedule shown in Table 2. The forgings are shown in Figure 25 after a 2400°F recrystallization heat treatment. The surface condition of all of the vanes was good with no evidence of any surface tears or cracks. Dimensional inspection of the forgings was conducted which included measurements of maximum pitch, trailing edge thickness and chord width. Eleven of the sixteen forgings were within tolerance (0.557-0.567 inch) for the maximum pitch, the other five being up to 0.007-inch greater in thickness than required. Measurements of the trailing edge thickness and chord width were inconsistent. Trailing edge thicknesses were greater than required while the chord widths were undersize (0.08 inch). Differences in thickness were anticipated for several reasons. The preform shapes in tool deflections, i.e., differences in metal fill. Setup was achieved with only one ODS alloy prior to forging all the ODS materials. Differences in the flow stress of the alloys could also affect tool deflections leading to changes in metal flow.

The first forging campaign was conducted primarily to determine if directional forging is a viable process and whether or not the preform designs selected could be formed into the HPT vane shape while still retaining the desired texture.

Evaluations of the forgings indicated that the microstructure was good for all forgings except the YDNiCrAl material which had been machined into the simple wedge shape, Figure 11C. The forgings were also found to be dimensionally stable after the 2400°F recrystallization heat treatment.

Results of this first forging campaign indicated that the directional forging approach is a viable process; however, changes in preform designs would be necessary to achieve complete fill in the trailing edge.

4.1.2 Second HPT Vane Forging Campaign Evaluation

Table 8 illustrates the schedule used for the second forging campaign. During the second forging campaign only MA754 preforms were forged because of unfavorable engine test and environmental resistance results obtained for the other two ODS alloys. The HPT vanes are shown after forging and grit blasting in Figure 26. Evaluations of the surface condition, surface integrity and dimensions were performed and are presented in Table 8. The surface condition was good although a pebbly surface was noted on those preforms coated with glass composition A. Glass composition B had been used for the first forging campaign. The differences in surface conditions are noted in Figure 27. The surface integrity was excellent for all forgings with no evidence of any cracks or tears.

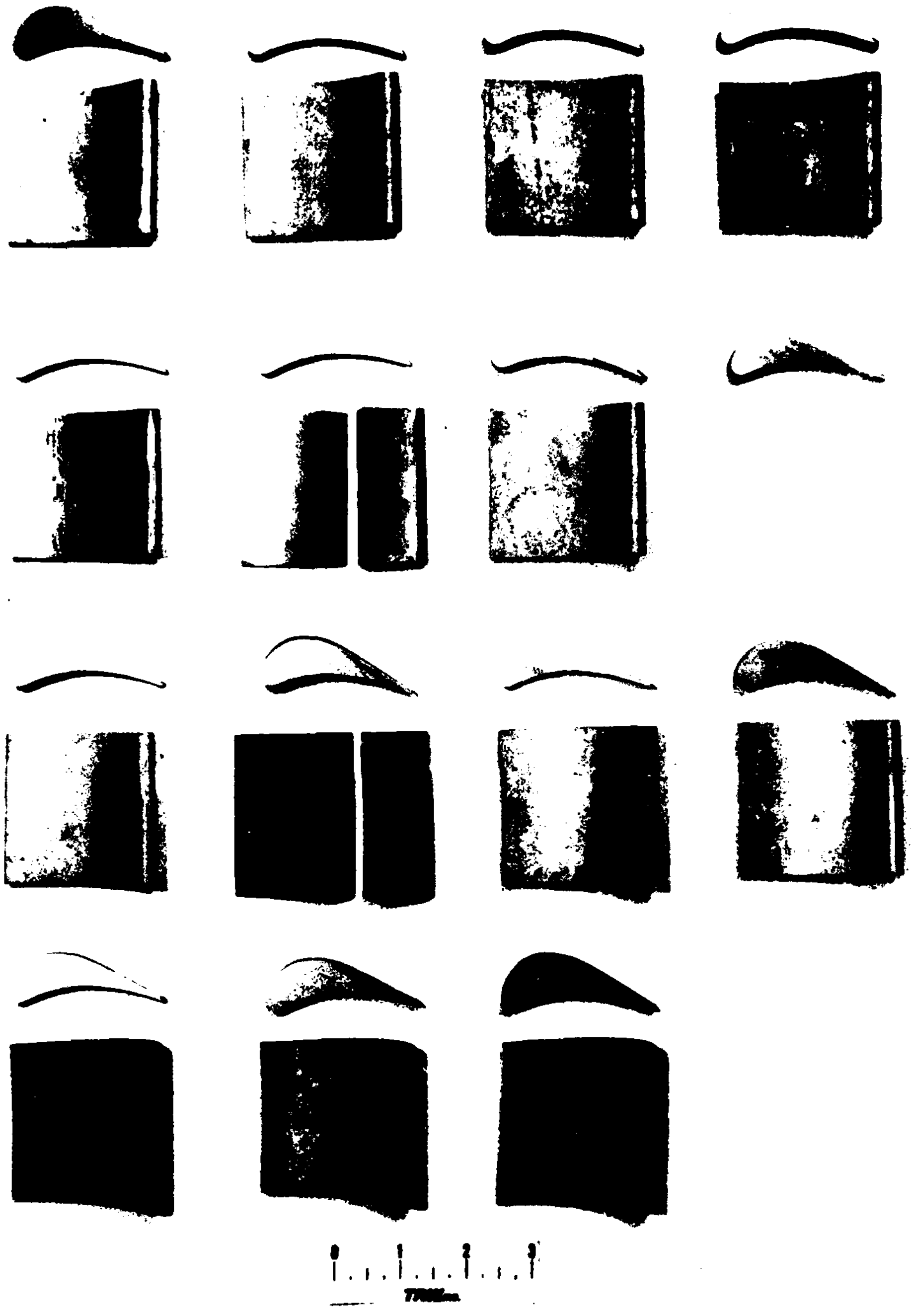


Figure 25 (a). Concave Side of Net Shape HPT Vanes Produced in Phase I, Campaign 1. See Table 2 for Identification. Photographed in Sequence 1-16

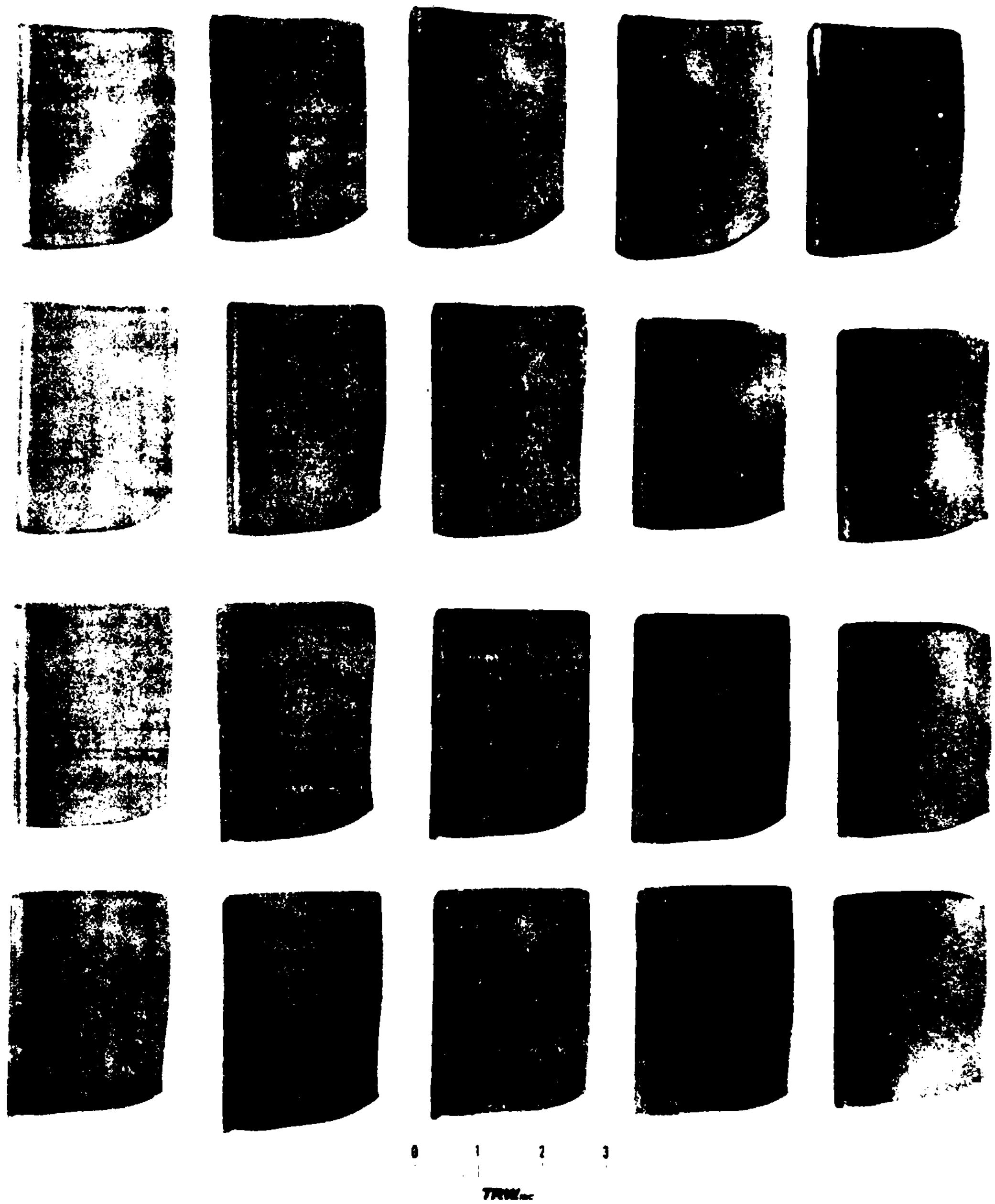


Figure 25 (b). Convex Side of Net Shape HPT Vanes Produced in Phase I, Campaign 1. See Table 2, for Identification. Photographed in Sequence 1-16

TABLE 8

TASK I CAMPAIGN II FORGING RESULTS

S/N	Preform Design (A)	Forge Temp (°F)	Observations (Grit Blasted) Surface	Integrity	Trail Edge Fill (B)	Grain Size	Defect Area (C)
1	1	1950	Pebbly	Good	1.4" TE fill		
2	1	1950	Pebbly	Good	Non-fill	Coarse	T/E and Central
3	2	1950	Pebbly	Good	1.4" TE fill		
4	2	1950	Pebbly	Good	Non-fill	Coarse	T/E and Central
5	3	1950	Pebbly	Good	2.1" TE fill		
6	3	1950	Pebbly	Good	1.6" TE fill	Coarse	T/E
7	4	1950	Pebbly	Good	1.6" TE fill		
8	4	1950	Pebbly	Good	Non-fill	Coarse	T/E
9	5	1950	Pebbly	Good	Non-fill		
10	5	1950	Pebbly	Good	Non-fill	Coarse	T/E
11	1	1850	Pebbly	Good	Non-fill	Medium	TE and Central
12	2	1850	Pebbly	Good	Non-fill	Medium	TE and Central
13	3	1850	Pebbly	Good	2.4"TE fill	Medium	TE
14	4	1850	Pebbly	Good	2.4"TE fill	Medium	TE
15	5	1850	Pebbly	Good	Non-fill	Medium	TE and Central
16	1	1750	Pebbly	Good	Non-fill	Fine	TE
17	2	1750	Pebbly	Good	1.6"TE fill	Fine	TE
18	3	1750	Pebbly	Good	2.3"TE fill	Fine	TE
19	4	1750	Pebbly	Good	2.1"TE fill	Fine	TE
20	5	1750	Pebbly	Good	Non-fill	Fine	TE

(A) Preform design - See Figures 12A & 12B
(B) Length of forging trailing edge with adequate chord length for vane
(C) Microstructural Defects: Higher modulus orientations generally 1/4" diameter localized areas

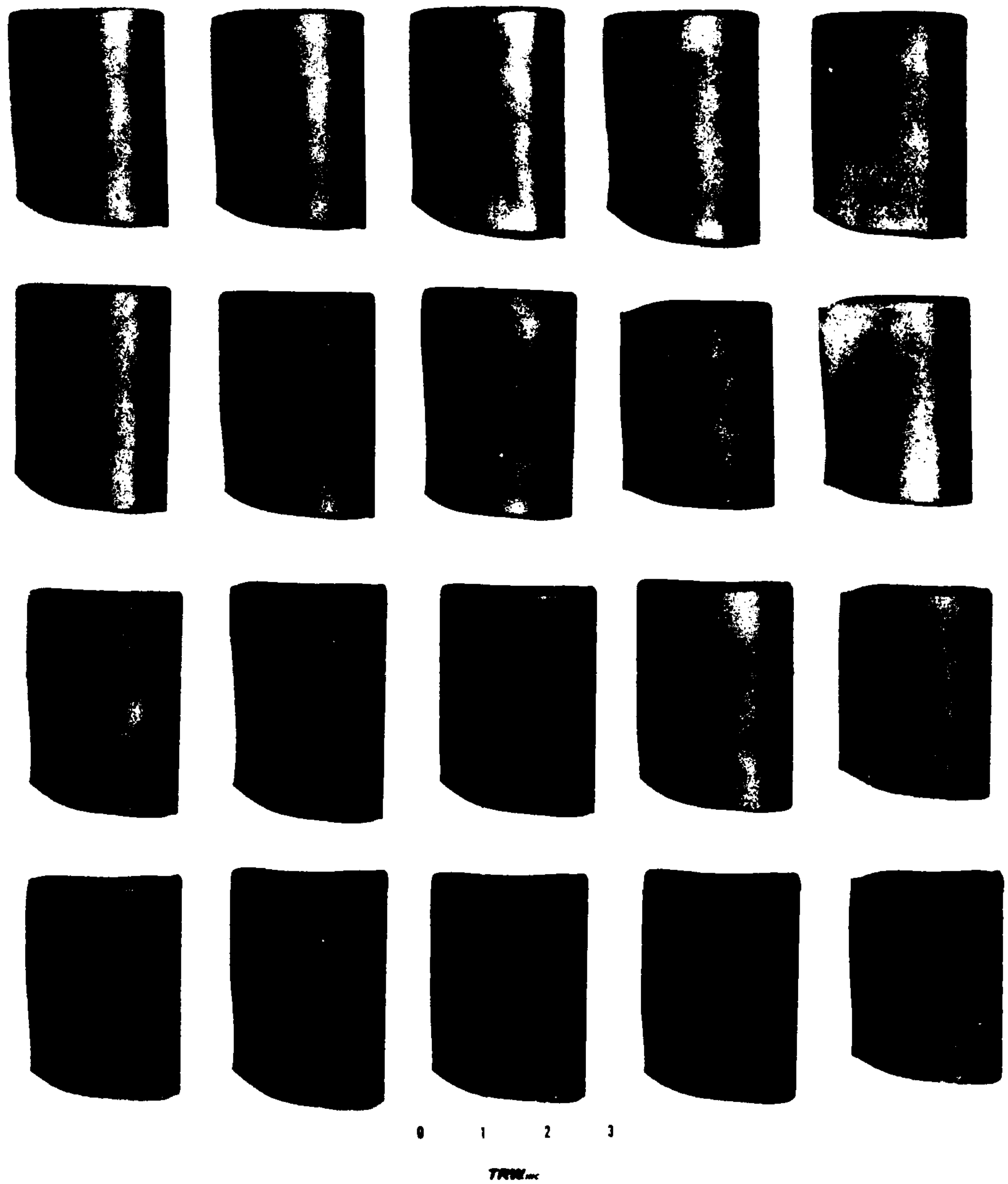


Figure 26 (a). Concave Side of Net Shape HPT Vanes Produced in Phase I, Campaign II. See Table 3 for Identification. Photographed in Sequence 1-20

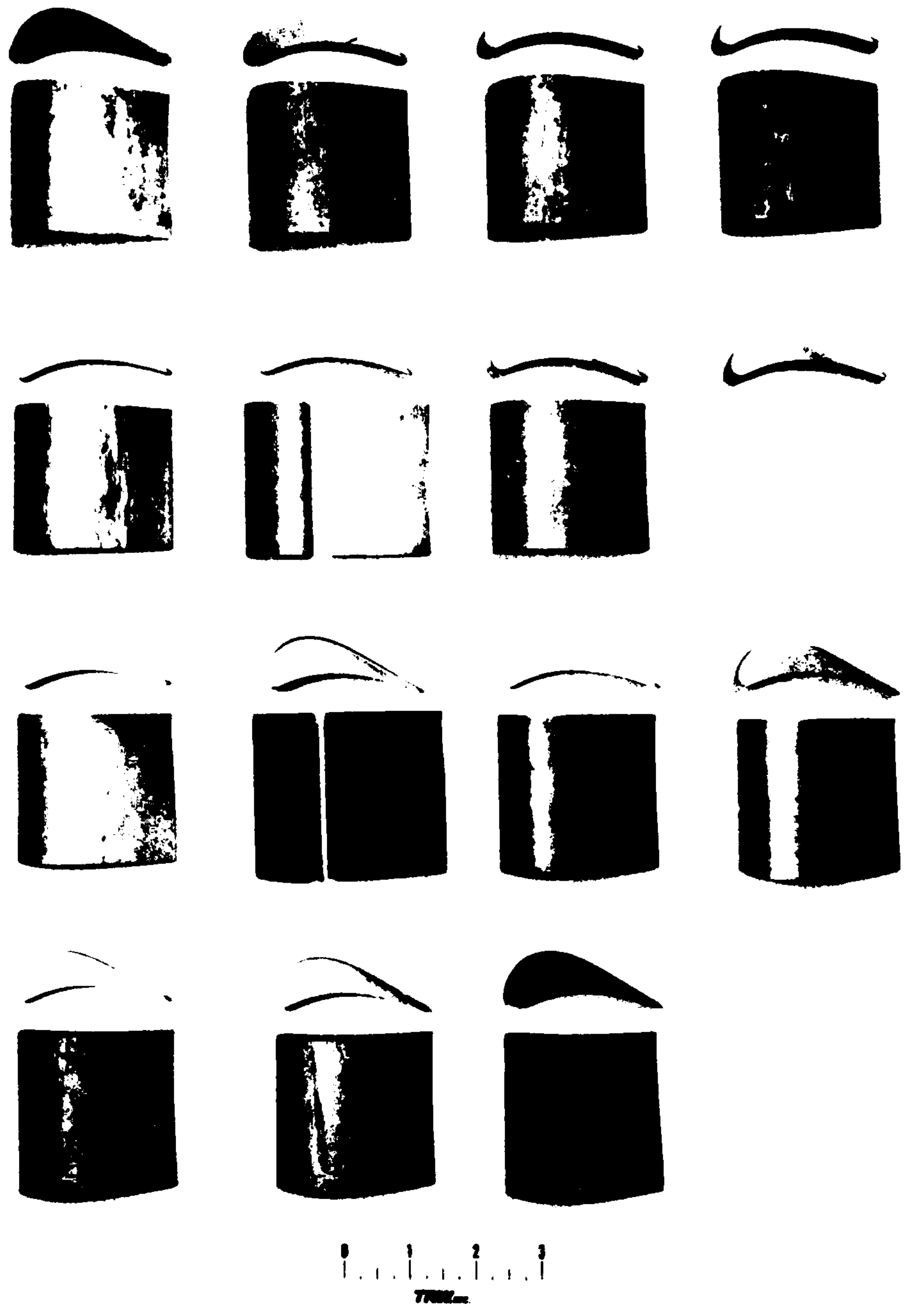


Figure 26 (b) Convex Side of Net Shape HPT Vanes Produced in Phase I, Campaign II. See Table 3 for Identification. Photographed in Sequence 1-20

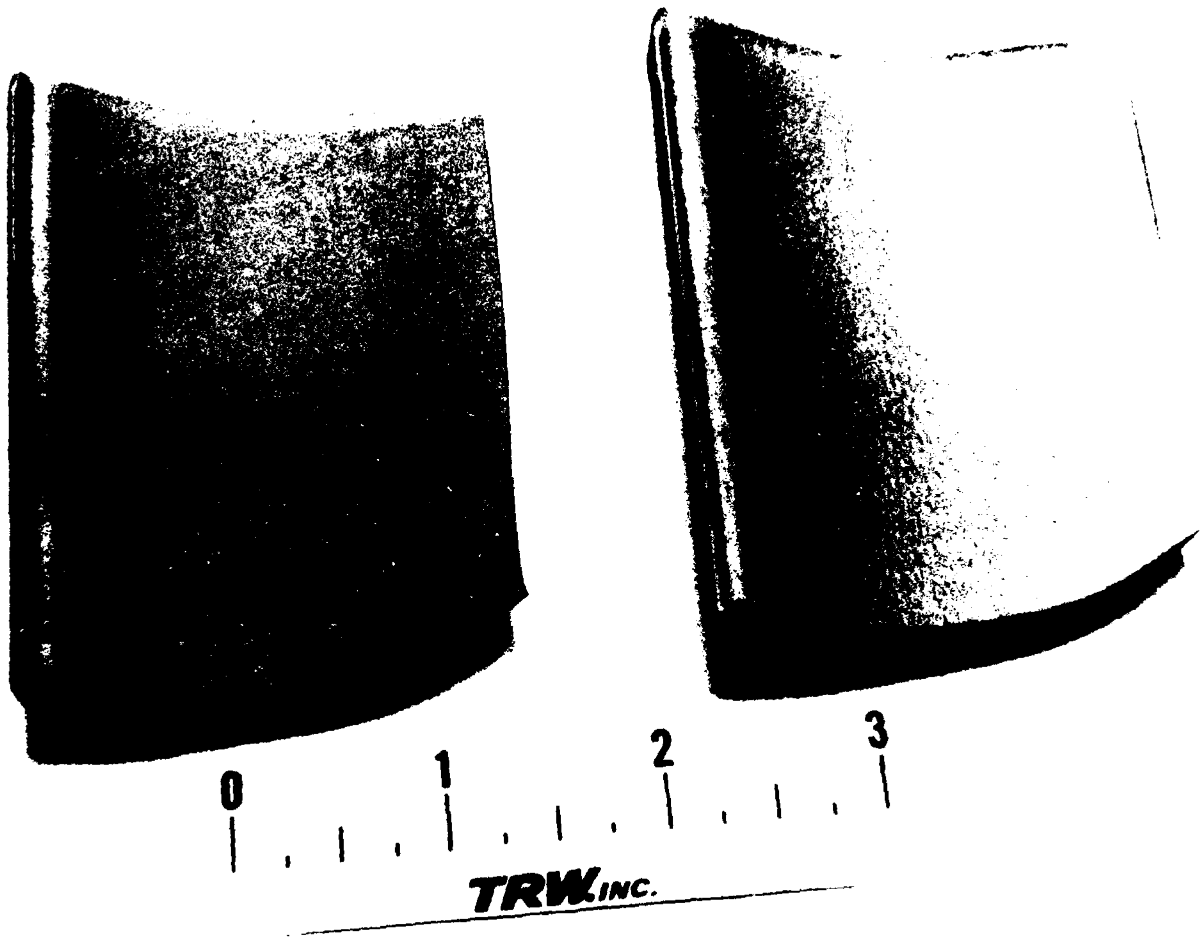


Figure 27. Surface Conditions After Forging and Grit Blasting. Note Pebbly Surface of Glass Coated A Forging

4.1.3 Phase II HPT Vane Forging Evaluation

The objectives of Phase II were to demonstrate reproducibility of the near-net shape vane forging process and produce for engine testing HPT vanes, LPT vanes and HPT bands.

Evaluations of the surface condition after forging indicated that most of the Design No. 1 preforms exhibited some superficial crazing on the convex side near the pitch thickness as indicated in Table 9 and Figure 28. Designs No. 2 and 3 forged very well. No crazing was detected. The reason for the crazing in the Design No. 1 forgings is not clearly understood. Possibly it was caused by lateral tensile strains produced by the lower forging reduction with this design. Lower forging reductions could reduce compressive work in the region that experiences the highest bending moment. Some of all the preform designs contained minor cracking, 1/8 X 3/8 inch, in localized end regions as also shown in Figure 28. It is believed the end cracking would have been eliminated had the preform edges in that region been radiused. Most of the forged parts were suitable for machining to finished vane shape.

The recrystallized macrostructures obtained were categorized as "good", "marginal" and "unacceptable". A "good" macrostructure is one that meets turbine vane specification requirements, i.e., "in the recrystallized and macroetched (Hydrochloric peroxide) condition, the cross-section normal to the process direction shall have a dull matte appearance with no significant differential etching effects and the modulus of elasticity shall not be greater than 25 X 10^6 psi." The term "marginal" describes a macrostructure which may be acceptable by modulus measurements but lacks a uniformly etched macrostructure. An unacceptable macrostructure is one that has an obviously strong etch mismatch and does not meet either the visual or modulus requirements. Macroetched transverse sections of forged vane close shapes showing representative macrostructures are presented in Figure 29. As can be seen in Table 9 the parts forged at 1800°F indicated inconsistent results. Macrostructures ranging from good to unacceptable were produced from each preform design. Although only preforms of Design No. 1 were forged at 1750°F the results were consistently good.

The vanes were inspected for dimensional reproducibility. The chord width, maximum pitch and trailing edge thickness were measured and are shown in Table 10. A precision 10 X cross sectional "eyelash" plot shown in Figure 30 was made and superimposed on finished part drawings, demonstrating that the as forged vane is dimensionally acceptable.

4.2 LPT VANE EVALUATION

The LPT vane near-net shapes are shown in Figure 31 after forming and grit blasting. In general, the surface condition was good except for a few surface irregularities. The exact cause of the irregularities is uncertain. They could be a result of the canning material left on during rolling, or they could be a result of interaction with the glass coating. Some evidence of surface crazing on the convex side was observed; however, these appear to be related to only the near surface and would not affect the machining of the vane from the near-net shaped vane.

Dimensional inspection indicated better reproducibility than for the first forging campaign possibly because only one alloy was forged and all preforms were of a wedge-shaped design. Pitch thickness measurements were reproducible, between 0.555 and 0.561 inches for those forged at 1950°F; between 0.550 and 0.552 for those forged at 1850°F; and between 0.552 and 0.557 for those forged at 1750°F. These measurements either met or were only slightly less than the blueprint requirement of 0.557-0.567 inches.

Since the forgings were not going to be used for finish machined hardware, no attempt was made at this time to "fine tune" the process to produce vanes meeting all blueprint specifications. The trailing edge thicknesses, measured 0.060-inch from the edge, were found to be between 0.30-0.41 inches for all twenty forgings, all quite reproducible.

Of the five forging design, Design No. 3 produced the best trailing edge fill since an additional 0.080-inch was added to the preform design. Design No. 5, the simple right triangle wedge shape produced the least amount of fill. Greater mass in the trailing edge of the preform, Design No. 4, was of some benefit; however, the material will flow in the direction of least resistance which means that movement towards the thin trailing edge area does not appear likely for the designs selected for the HPT vane. Several of the forgings were inspected in a production vane guillotine gage and were found to be within tolerances of the part drawing.

It was found that process temperature was the major contributing factor affecting recrystallization. Mistextured areas were found in the maximum pitch area in forgings produced at 1950° and 1850°F but were not found in forgings produced at 1750°F. All forgings showed some evidence of mistexture in the trailing edge region. The trailing edge undergoes the most work because of the preform design and in addition has a greater degree of "cold work" due to the greater heat loss in this area during transfer. A summary of the forging results and recrystallization response is shown in Table 8.

Based on the results of the two forging campaigns it was concluded that vanes can be forged from simple wedge shaped preforms; however, the simple wedge shape does not appear to allow complete trailing edge fill. In addition heavy work in the trailing edge regions causes a mistextured microstructure.

TABLE 9

PHASE II MA754 HPT VANE NNS PROCESSING RESULTS

S.N.	Heat I.D. (1)	Preform Design (2)	Forging Temperature, °F	Crazing (3)	Macrostructural Assessment (4)
1	A	1	1800	No	Good
2	A	3	1800	No	Good
3	A	2	1800	No	Good
4	A	1	1800	Yes	Marginal
5	A	1	1800	Yes	Unacceptable
6	A	1	1800	Yes	Good
7	A	1	1800	Yes	Marginal
8	A	1	1800	Yes	Unacceptable
9	A	1	1800	Yes	Marginal
10	A	1	1800	Yes	Unacceptable
11	A	1	1800	-	TRW Retained
12	A	2	1800	-	TRW Retained
13	A	2	1800	None	Marginal
14	A	2	1800	None	Not yet Rx'd
15	A	2	1800	None	Good
16	A	2	1800	None	Marginal
17	B	1	1800	None	Good
18	B	2	1800	None	Good
19	B	2	1800	None	Marginal
20	B	2	1800	None	Undersize Preforms
21	B	2	1800	None	Undersize Preforms
22	B	3	1800	None	Good

TABLE 9

PHASE II MA754 HPT VANE NNS PROCESSING RESULTS (CONT'D)

S.N.	Heat (1) I.D.	Preform (2) Design	Forging Temperature, °F	Crazing (3)	Macrostructural Assessment (4)
23	B	3	1800	None	Good
24	B	3	1800	None	Unacceptable
25	B	3	1800	None	Unacceptable
26	A	3	1800	None	Not Yet Rx'd
27	A	3	1800	None	TRW Retained
28	A	3	1800	None	Good
29	A	3	1800	None	Marginal
30	A	3	1800	None	Good
31	A	1	1750	Yes	Good
32	A	1	1750	Yes	Good
33	A	1	1750	Yes	Good
34	A	1	1750	Yes	Good
35	A	1	1750	Yes	Good
36	A	1	1750	Yes	Good
37	A	1	1750	Yes	Good
38	A	1	1750	Yes	Good
39	A	1	1750	Yes	Good
40	B	1	1750	None	Undersize Preform

(1) Heat A - D104A2B2-1, Heat B - DT0076B1-2
(2) Refer to Table I.
(3) Refer to Figure 9.
(4) Refer to Figure 10.

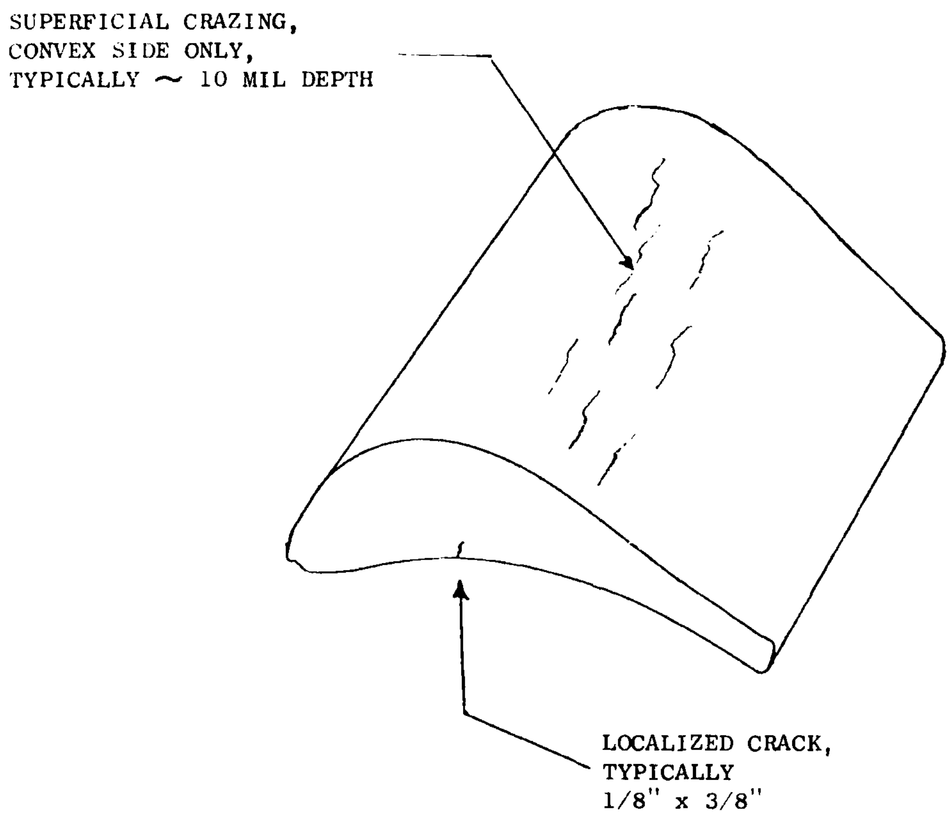


Figure 28. Forging Defect Locations In HPT Vane NNS

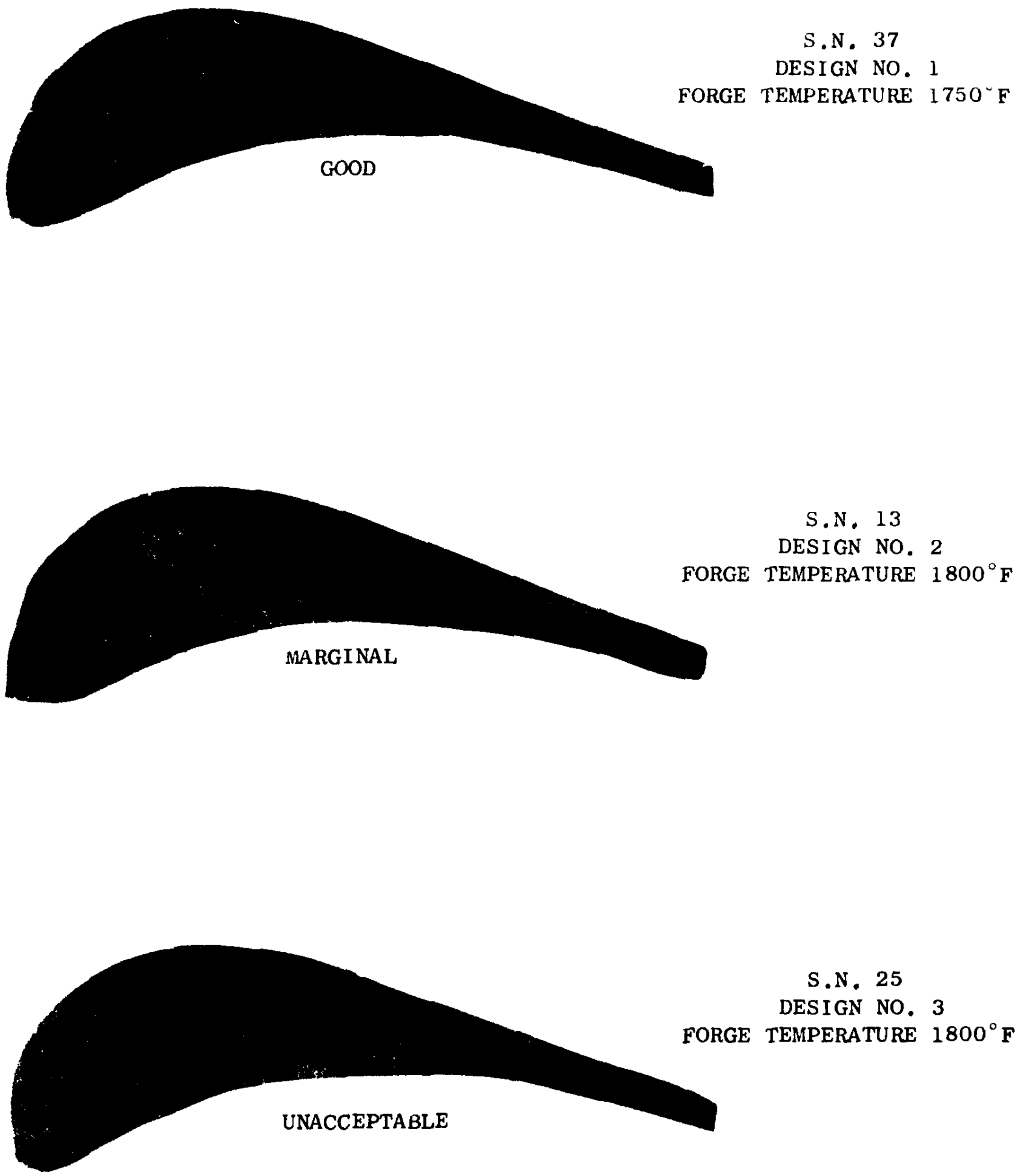


Figure 29. Representative Macrostructures of Forged HPT Vane NNS

TABLE 10

DIMENSIONAL INSPECTION DATA OF PHASE 11 FORGED HPT VANES [a]

S/N	Preform [b] Design	Chord Width (Inches)	Maximum Pitch (Inches)	T.E. Thickness (Inches)
4	1	2.702	.650	.150
5	1	2.735	.650	.152
6	1	2.706	.650	.155
7	1	2.702	.650	.151
8	1	2.721	.650	.151
9	1	2.718	.650	.152
10	1	2.722	.650	.150
11	1	2.728	.649	.152
12	2	2.780	.659	.163
13	2	2.775	.650	.159
14	2	2.780	.656	.159
15	2	2.779	.662	.164
16	2	2.774	.657	.160
17	1	2.725	.649	.151
18	2	2.778	.656	.157
19	2	2.778	.655	.155
20	2	(c)	-	-
21	2	(c)	-	-
22	3	2.779	.655	.157
23	3	2.790	.655	.160
24	3	2.790	.657	.161
25	3	2.779	.651	.157
26	3	2.796	.655	.161
27	3	2.781	.651	.163
28	3	2.796	.658	.162
29	3	2.795	.656	.162
30	3	2.790	.657	.162
31	1	2.760	.641	.139
32	1	2.757	.642	.140
33	1	2.745	.637	.139
34	1	2.767	.643	.143
35	1	2.743	.636	.139
36	1	2.761	.635	.140
37	1	2.763	.635	.138
38	1	2.756	.636	.140
39	1	2.770	.638	.140
40	1	(c)	-	-

(a) Measurements Made with Hand Micrometers - at a Section 0.25-Inches from End of Forging.
(b) Refer to Figure 10.
(c) Undersize Preforms.

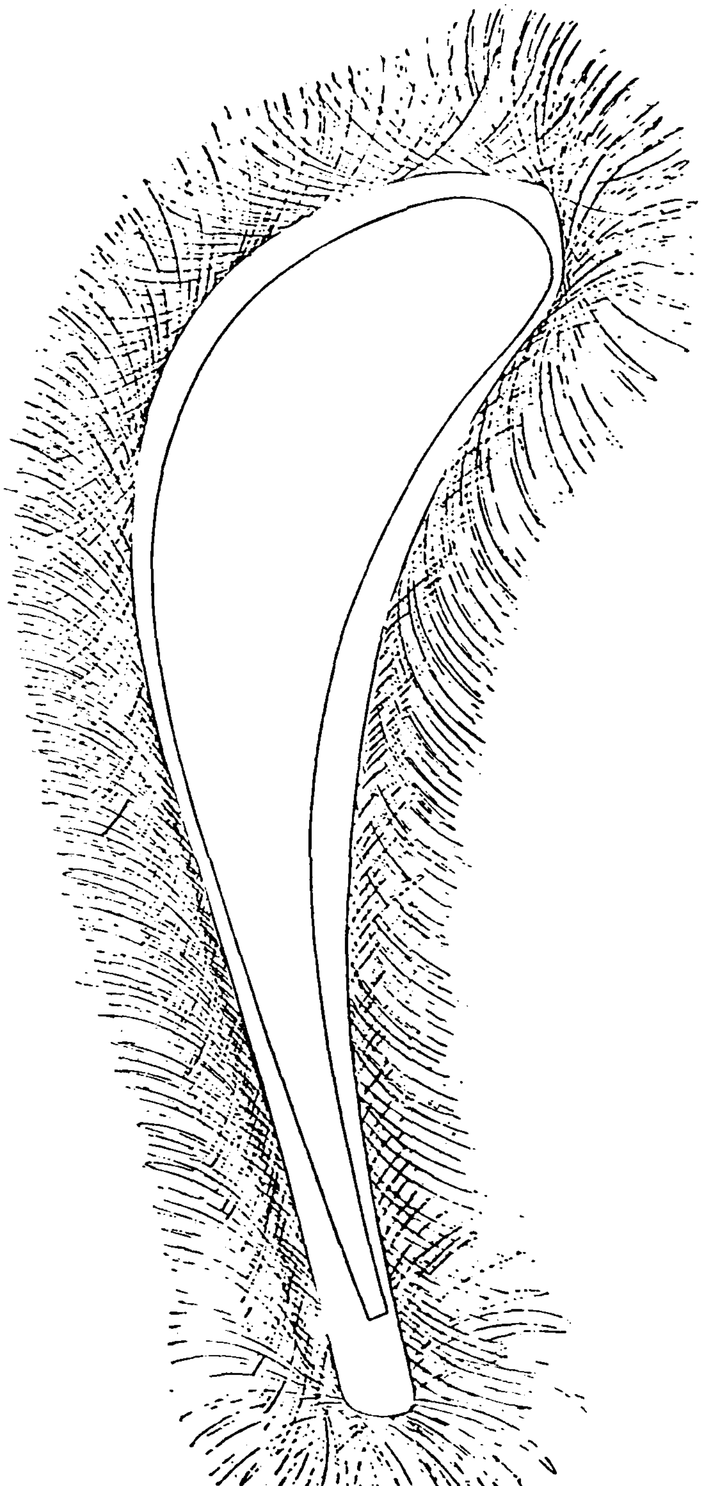


Figure 30. "Eyelash" Vane Cross Section Plots

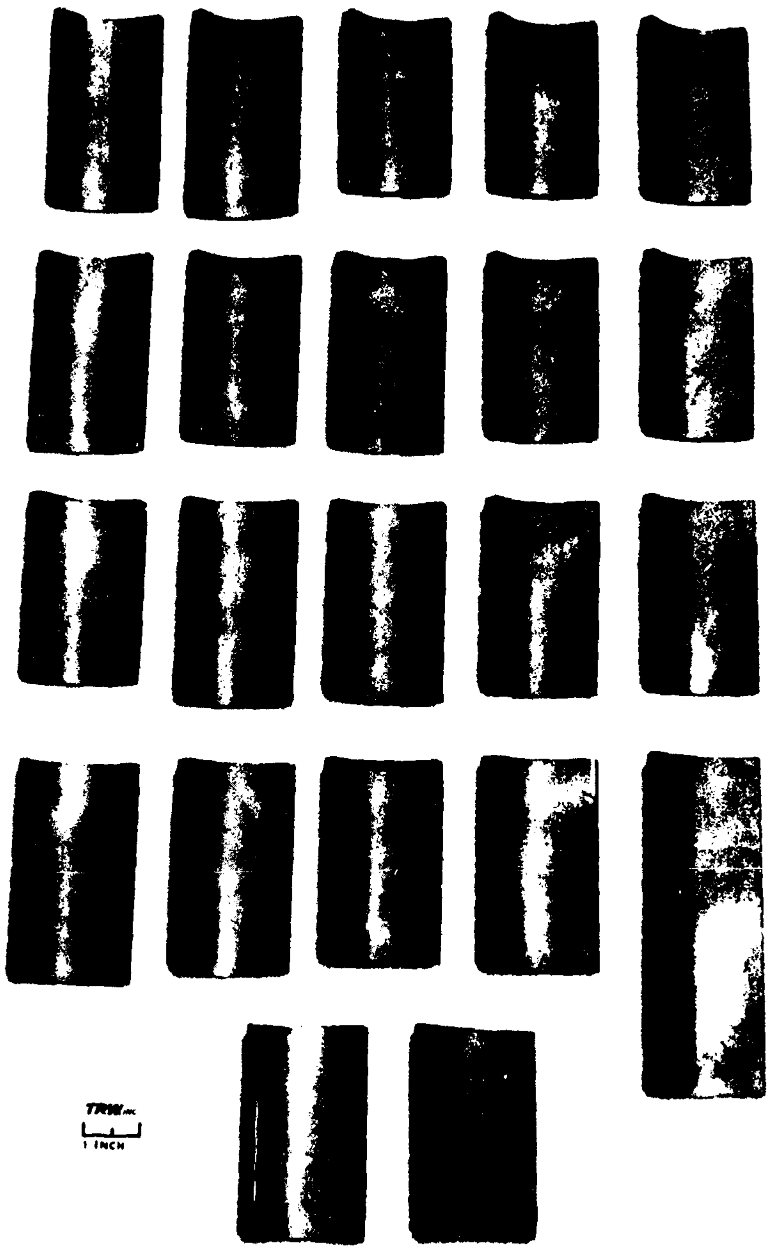


Figure 31A. Concave Side of Near-Net LPT Vane Shapes. See Table 5 for Identification. Photographed in Sequence 1-22

Figure 31B. Convex Side of Near-Net LPT Vane Shapes. See Table 5 for Identification. Photographed in Sequence 1-22

The vane blanks were recrystallized at 2400°F for one hour and the ends polished and macroetched in Hydrochloric and peroxide. All but three of the preform blanks that were rolled at 1650°F prior to forging had good macrostructures. The preform blanks rolled at 1850°F had a very coarse grain structure of high modulus orientation. A photo showing a NNS vane containing typical fine grain macrostructure and one showing an area of mistexture is shown in Figure 32. A photo demonstrating the coarse and mistextured macrostructure of a NNS vane rolled at 1850°F is shown in Figure 33 along with an as formed NNS vane blank.

4.3 HPT BAND EVALUATION

The near-net shape bands are shown in Figure 34 after forming and grit blasting. The configuration of the near-net band shape was found to be good. No evidence of crazing was observed, but surface irregularities were particularly severe for the band forging. The cause is not certain but is probably due to canning material left on during rolling or a glass coating reaction during forming.

The overall surface conditions of the HPT band near-net shapes were assessed in the unrecrystallized condition. Four NNS band blanks were considered poor from what was probably a glass coating reaction. Three other blanks were ranked as fair because they exhibited some surface reaction and the remainder were ranked as good. A photo of a NNS band is shown in Figure 35.

A macro evaluation of the NNS bands resulted in a somewhat larger grain size than as received MA754 bar. A micro evaluation is discussed in a later section.

4.4 METALLOGRAPHIC EVALUATION OF HPT VANES, HPT BANDS AND LPT VANES

HPT Vanes

Most of the vanes forged at 1750 & 1800°F contained small isolated areas of mistexture while others forged at 1800°F contained larger misoriented areas. Photo micrographs are shown in Figure 36. It is not clearly understood why the forged vanes contained these isolated areas of mistexture, however thermal fatigue and dynamic modulus data did not reflect this condition until a large area of misoriented grains were intentionally placed in the specimen. This demonstrates that the test material is tolerant of small amounts of mistexture.

LPT Vanes & HPT Inner Bands

The LPT vanes and bands were rolled and recrystallized under similar conditions. The bands had a slightly larger grain size and contained large areas of mistexture at the cross sectional center of the band blank. All but three of the LPT vane blanks rolled at 1650°F recrystallized normally. Photomicrographs showing areas of mistexture in bands and normal texture in LPT vanes are shown in Figure 37.

LPT Vane #6
2X
Typical Fine Grain
Macrostructure
Rolled at 1650°F

LPT Vane #5
2X
Area of Mistexture
Rolled at 1650°F

Figure 32. LPT Vane NNS Macrostructures

LPT VANE NO. 21

2X

ROLLED @ 1850°F
LARGE MISTEXTURED
GRAIN STRUCTURE

LPT NNS
VANE BLANK
AS FORGED BENT

Figure 33. LPT Vane Near-Net Shape

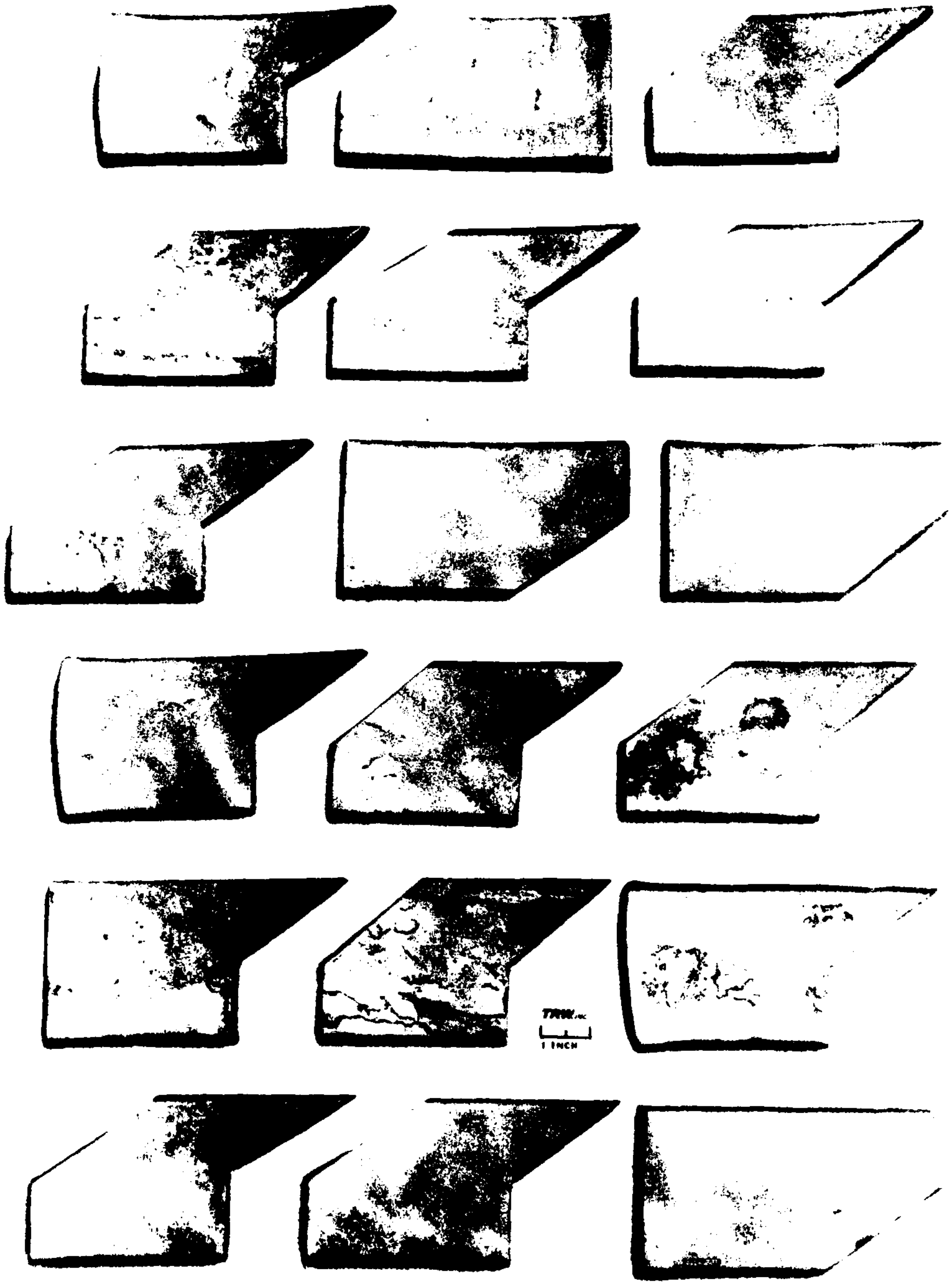
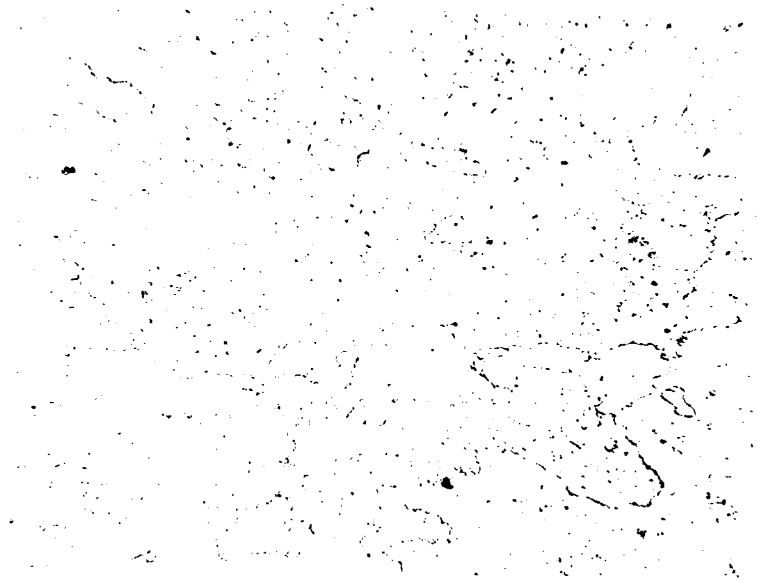
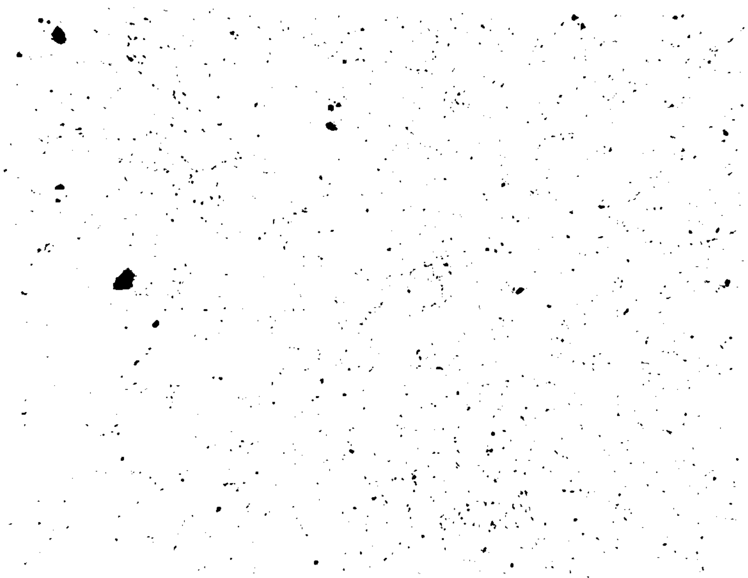


Figure 34. Near-Net Shape HPT Bands Photographed in Sequence 1-18

Figure 35. NNS Band Prior to Machining



MT NO. 9-738
1750°F FORGE TEMP



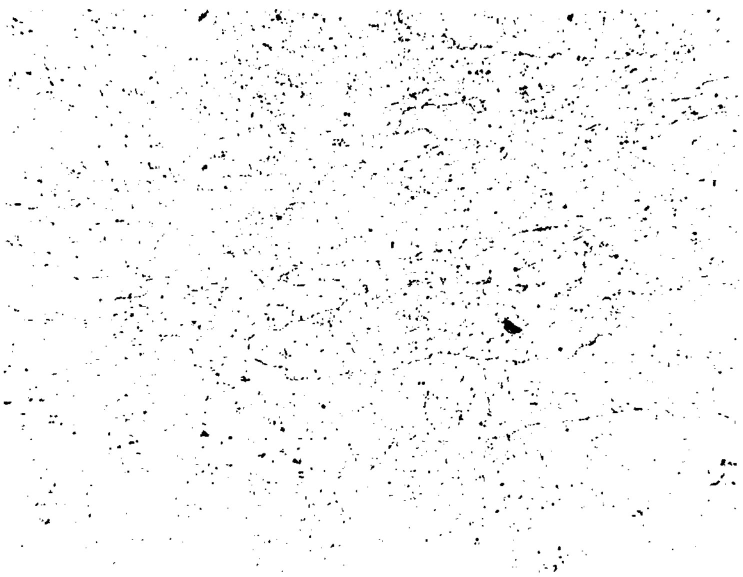
MT NO. 9-735
1800°F FORGE TEMP

100X

Figure 36. NNS HPT Section

MT NO. 9-741 LPT VANE
1650°F ROLL TEMP.

PHOTO MICROGRAPH
SHOWING GOOD TEXTURE
HEAT TREAT 2400°F/1 HR



MT NO. 9-744 HPT BAND
ROLL TEMP. 1650°F

HEAT TREAT 2400°F/1HR

HIGH MODULUS AREA

Figure 37. NNS HPT Vane & Band

In order to determine the reason for the mistexture in the band blanks, a section of MA754 unrecrystallized bar was processed under the same conditions as the LPT vane and band blanks with the exception of the heat treatment. It was discovered that too rapid heatup in recrystallizing can form non <100> high modulus grains (2400°F 1 Hr/AC). A slower heatup rate was tried, and the material recrystallized normally.

The phenomenon was observed to a minor degree in as received unrecrystallized Huntington bar and to a major degree in material hot rolled for this investigation. Figure 38 demonstrates the effect of heatup rate on the recrystallization response. The mistextured areas in the NNS band blanks will not be detrimental to the life of the vane segment because the problem area has been removed during band machining.

1X 1X

STANDARD BAR ROLLED @ 1650°F 40% REDUCTION

DIRECT INSERTION 2400°F - 1 HR HOLD

STANDARD BAR ROLLED @ 1650°F 40% REDUCTION

STABILIZE AT 2000°F THEN HEAT
TO 2400°F IN 2 HRS - 1 HR HOLD

Figure 38. Effect of Heatup Rate on Recrystallization Response

SECTION V

MECHANICAL PROPERTY TESTING

5.1 PHASE I HPT VANE TESTING

Selected stress rupture and thermal fatigue tests were conducted on the HPT vane material from the second forge campaign. The testing schedule and specimen location are shown in Table 11. The stress rupture results in the longitudinal and short transverse direction are equivalent to or slightly better than standard MA754 bar. The results are shown in Figure 39.

Thermal fatigue results appear to be equal to or better than standard MA754 bar. The results are shown in Figure 40.

5.2 PHASE II TESTING

The NNS test plan included tensile testing at RT, 1600, 1800 and 2000°F, stress rupture testing at 1600, 1800 and 2000°F, dynamic modulus and thermal fatigue evaluation.

5.2.1 Test Specimens Near-Net Shape HPT Vanes

Longitudinal specimens were taken from the HPT vane along the axis of material flow. The transverse specimens were obtained from the bend area of the vane which is a combination of long transverse and short transverse directions. The sketch below demonstrates how the specimens were removed.

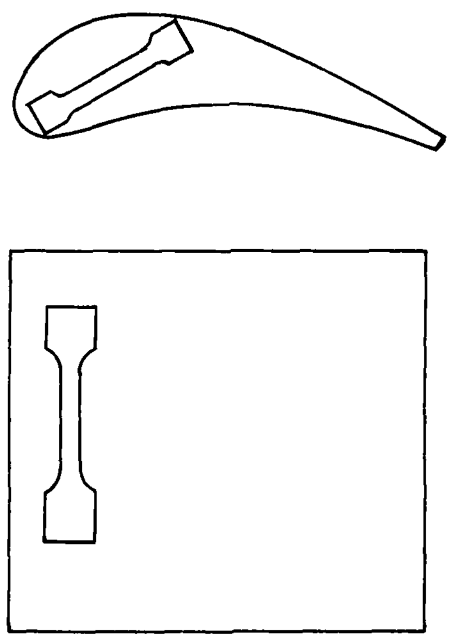


TABLE 11

MA754 PHASE I FORGED VANE MECHANICAL PROPERTIES EVALUATION - 2000°F

			SETS				
S.N.	Forge Temperature, °F	Preform Design	TE-X	TE	LE	Stress Rupture	LCF
4 A&B	1950	2		L[a]	L	(2) L	
6 A&B	1950	3		L	L	(2) L	
8 4 C's	1950	4				(4) ST[b]	
10 A&B	1950	5		L	L	(2) L	
5	1950	3					
16	1750	1	L				
18 A&B	1750	3		2 L	L	(2) L	
20	1750	5	L				

(a) Longitudinal

(b) Short Transverse

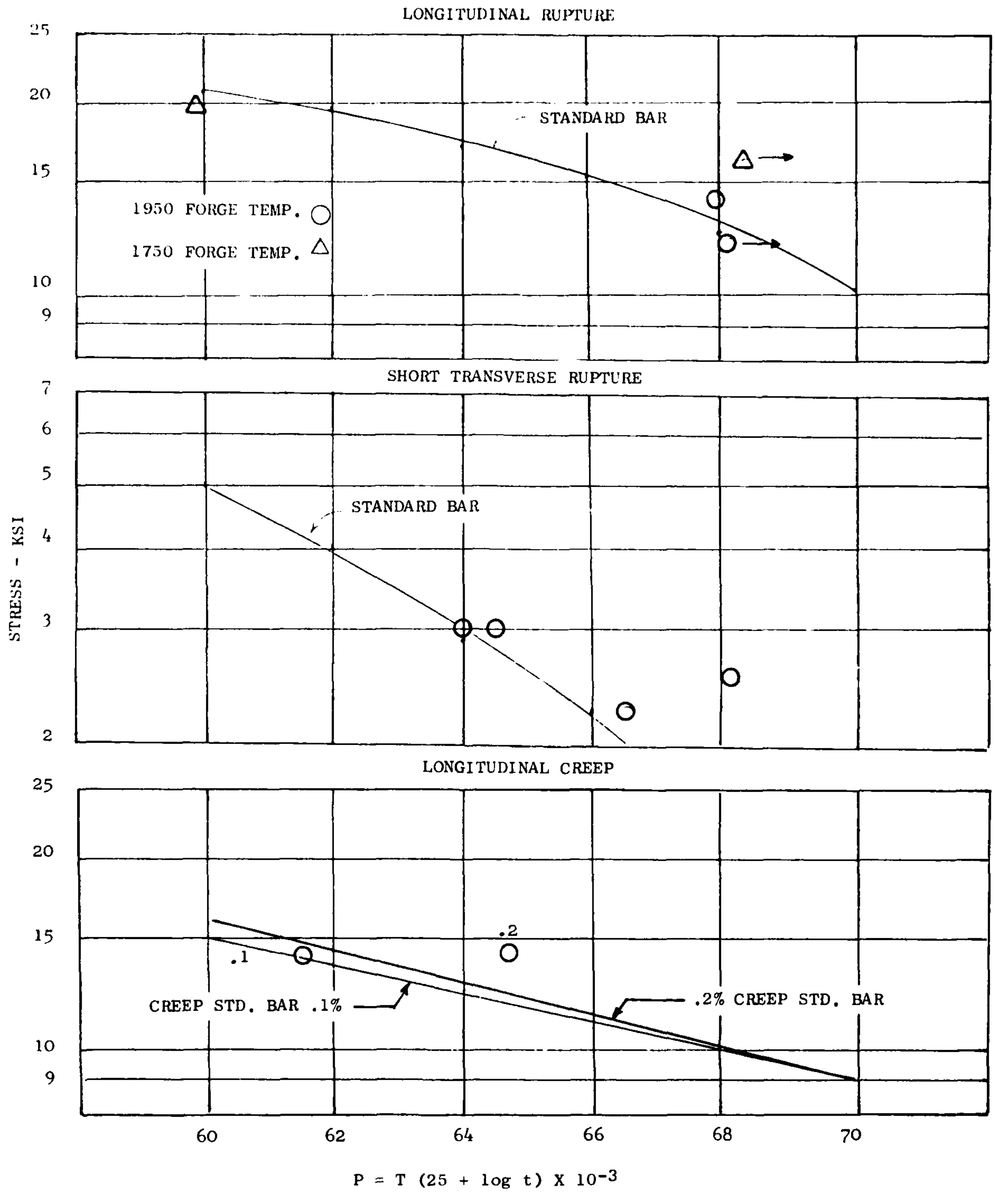


Figure 39. Creep and Rupture **Results** Forged MA754

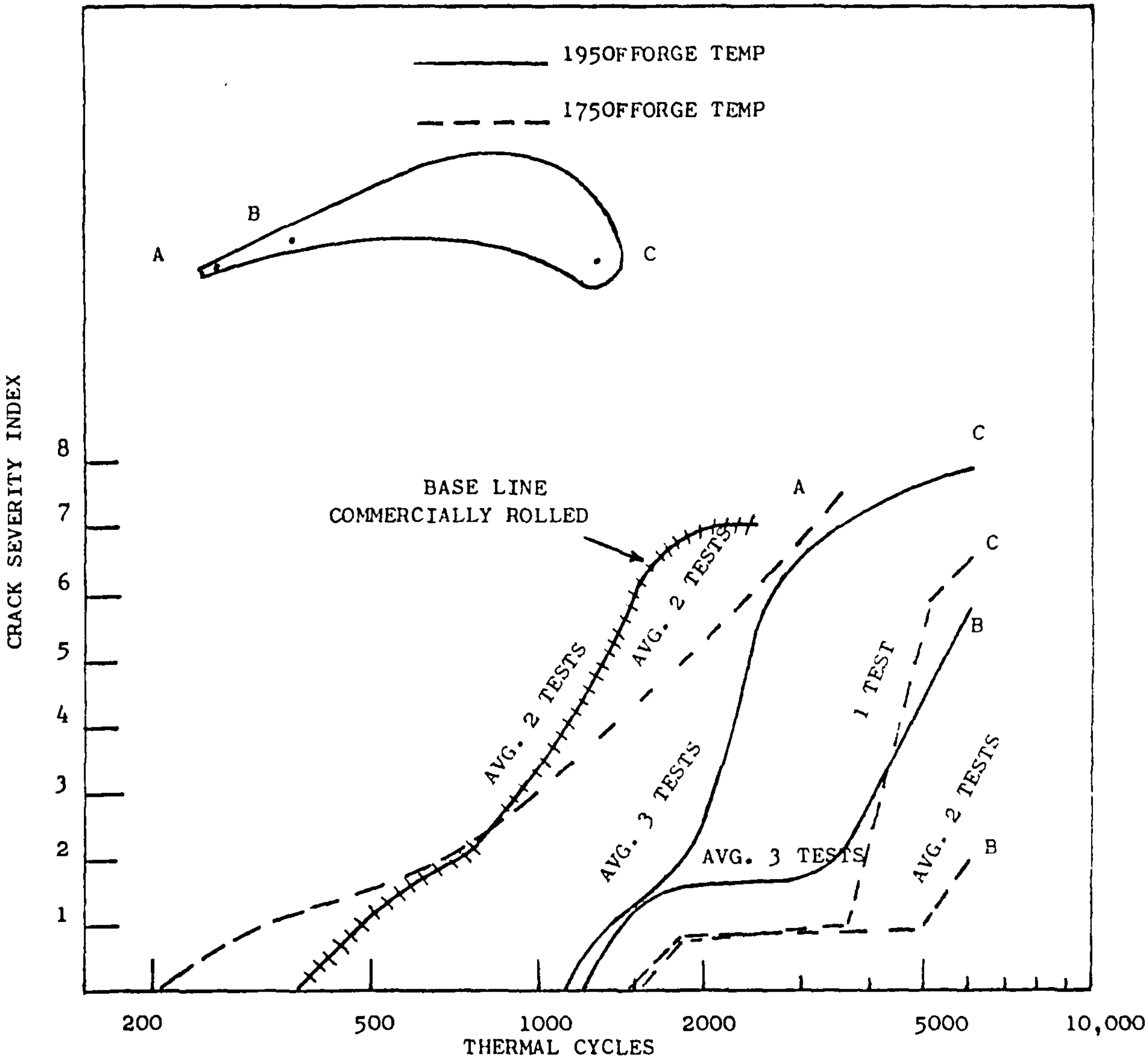


Figure 40. MA754 Forged Vane Simulated Engine Thermal Shock Evaluation

Near-Net Shape LPT Specimens

Longitudinal samples were removed from the LPT vane bent stock in the plate rolling direction. Specimens were tested from both the straight and bend areas. The transverse specimens removed from the bend area, required end extensions to be brazed on because of insufficient length. Figure 41 shows the manner in which the samples were removed along with a photo of a finish machined extended end specimen. B93 alloy was used for brazing the ends.

Near-Net Shape HPT Inner Bands

The longitudinal samples were taken in the rolling direction of the inner band rolled and forge bent plate. Transverse specimens were obtained from the long transverse direction. Figure 42 shows the specimen locations and orientations.

5.2.2 Test Plan

The test plan for the evaluation of MA754 near-net shape HPT vanes. HPT bands, and LPT vanes is outlined in Table 12.

TABLE 12

TEST PLAN FOR EVALUATION OF MA754 HPT VANES, HPT BANDS, AND LPT VANES

HPT VANES

Test	Temp. °F.	Number	Type
Tensile	75	4	Longitudinal
"	1600	4	Longitudinal
"	1800	4	Longitudinal
"	1800	4	Transverse
"	2000	4	Longitudinal
"	2000	4	Transverse
Rupture	1600	4	Longitudinal
"	1800	8	Longitudinal
"	1800	4	Transverse
"	2000	8	Longitudinal
"	2000	4	Transverse
Thermal Fatigue	2000	3	Preform Design 1 (1750°F)
" "	2000	3	Preform Design 3 (1800°F)
Modulus	2000	1	Preform Design 1 (1750°F)
"	2000	1	Preform Design 3 (1800°F)

TABLE 12 (Continued)

HPT BANDS

Test	Temp. °F.	Number	Type
Tensile	75	1	Longitudinal Band #13
"	1600	1	Longitudinal Band #13
"	1800	1	Longitudinal Band #13
"	1800	1	Transverse Band #13
"	2000	1	Longitudinal Band #13
"	2000	1	Transverse Band #13
Rupture	1600	1	Longitudinal Band #11
"	1800	2	Longitudinal Band #11
"	1800	2	Transverse Band #11
"	2000	2	Longitudinal Band #11
"	2000	2	Transverse Band #11
Thermal Fatigue	2000	2	Longitudinal - Long. Trans.
" "	2000	2	Longitudinal - Short Trans.
" "	2000	2	Standard MA754 Material
Modulus	2000	1	

LPT VANES

Test	Temp. °F.	Number	Type
Tensile	1800	1	Longitudinal - Vane #22 (1850°F)
"	2000	1	Longitudinal - Vane #22 (1850°F)
Tensile	1800	1	Longitudinal - Vane #10 (1650°F)
"	1800	1	Transverse - Vane #10 (1650°F)
"	2000	1	Longitudinal - Vane #10 (1650°F)
"	2000	1	Transverse - Vane #10 (1650°F)
Tensile	75	1	Longitudinal - Vane #17 (1650°F)
"	1600	1	Longitudinal - Vane #17 (1650°F)
Rupture	1600	1	Longitudinal - Vane #2 (1650°F)
"	1800	2	Longitudinal - Vane #2 (1650°F)
"	1800	2	Transverse - Vane #2 (1650°F)
"	2000	2	Longitudinal - Vane #2 (1650°F)
"	2000	1	Transverse - Vane #2 (1650°F)
"	1800	1	Longitudinal - Vane #12 (1650°F)
"	2000	1	Longitudinal - Vane #12 (1650°F)
Thermal Fatigue	2000	1	Vane #8 (1650°F) Bend
" "	2000	1	Vane #8 (1650°F) Straight
" "	2000	1	Vane #9 (1650°F) Mixture
" "	2000	1	Vane #9 (1850°F) Straight
Modulus	2000	1	Vane #8 (1650°F) Straight
"	2000	1	Vane #8 (1650°F) Bend
"	2000	1	Vane #8 (1850°F) Straight

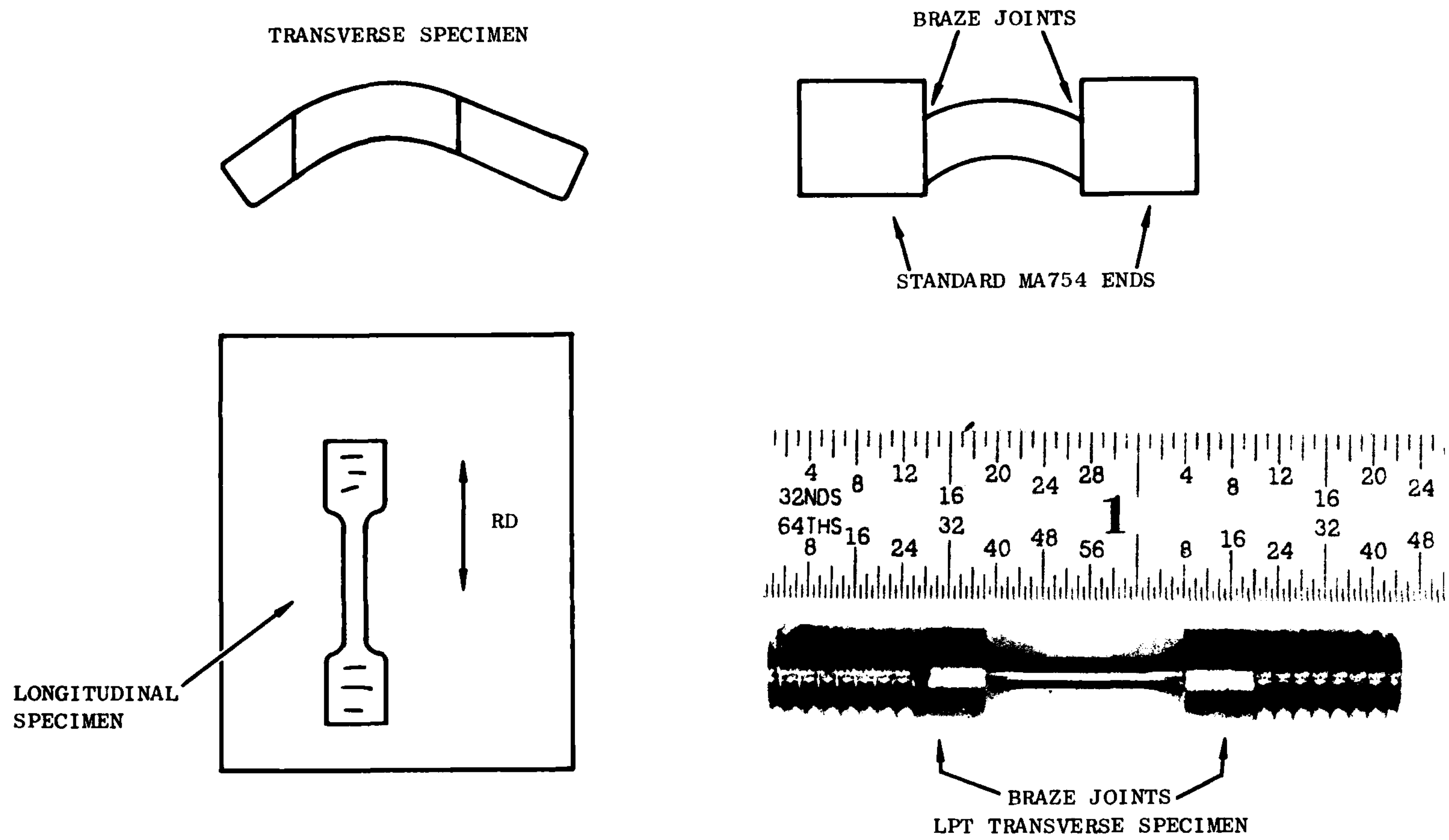


Figure 41. LPT Vane Test Speciment Location and Construction

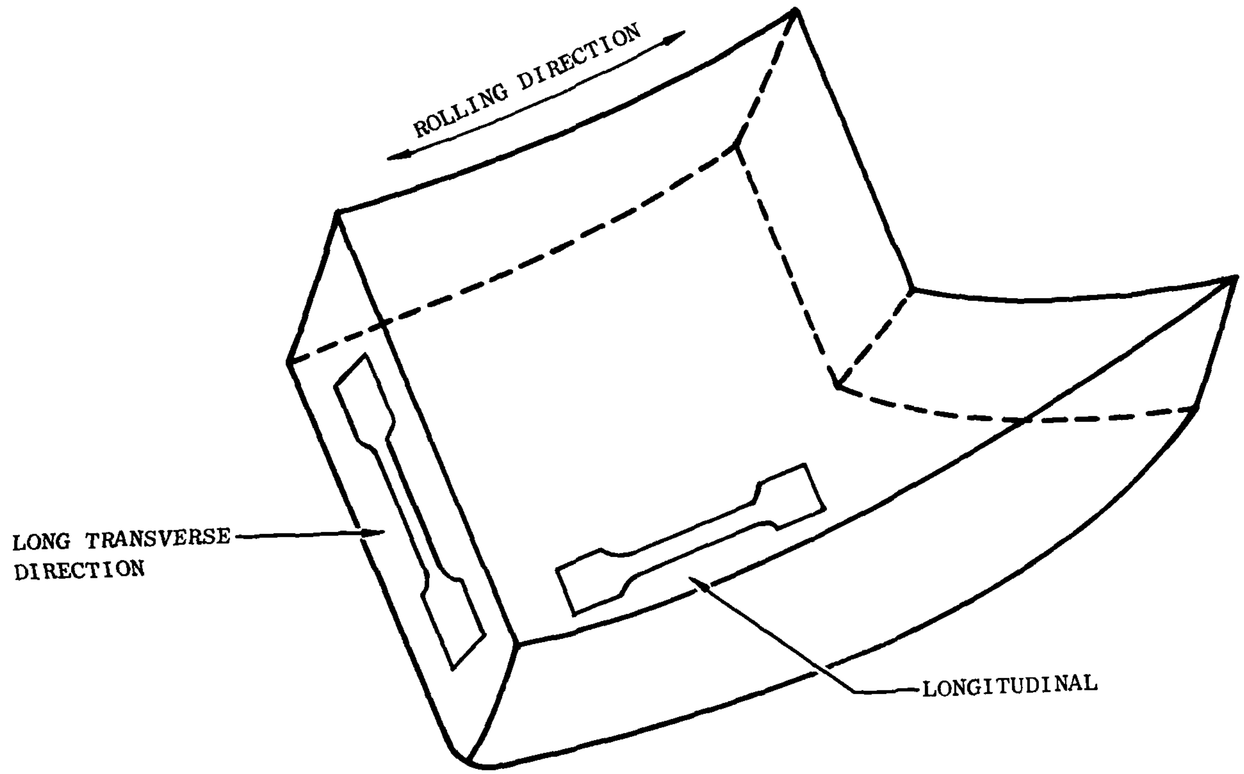


Figure :2. HPT Inner Band Test Specimen Location

5.2.3 Test Results

Tensile Results

HPT Vanes

Longitudinal tensile properties were obtained at room temperature, 1600, 1800, and 2000°F. Transverse properties were obtained at 1800 and 2000°F. The results of secondary working (forging) had no adverse effects on tensile properties. NNS longitudinal results met or exceeded conventionally processed MA754 bar. The varying of preform designs did not appear to have any significant effect on tensile properties in either longitudinal or transverse direction. The tensile results are listed in Table 13 and shown graphically in Figure 43 with NNS data plotted against standard MA754 properties.

LPT Vanes and HPT Bands

Longitudinal tensile properties · :e determined at room temperature, 1600, 1800, and 2000°F. Transverse properties were determined at 1800 and 2000°F. The tensile results of both the LPT vanes and HPT bands in the longitudinal and transverse directions met or in most cases exceeded the conventional MA754 rectangular bar properties. The results of the LPT vanes rolled at 1850°F and tested in the longitudinal direction are comparable to the vanes rolled at 1650°F and standard MA754 test results. The NNS tensile results of the LPT vanes and HPT bands are presented in Table 14. Figure 44 graphically demonstrates the NNS data vs conventional MA754 curve.

Stress Rupture Results
HPT Vanes, LPT Vanes & HPT Inner Bands

The stress rupture properties of all the NNS components were very similar. The stress rupture data are presented in Tables 15, 16, 17 and Figures 45 and 46. Testing was conducted at 1600, 1800 and 2000°F in the longitudinal direction and 1800 and 2000°F in the transverse direction. It appears that secondary working (rolling, forging) enhanced the properties of NNS MA754. The properties in both directions meet or exceed average data generated for standard MA754 rectangular bar.

Thermal Fatigue Testing

Thermal fatigue testing was conducted in a Simulated Engine Thermal Shock (SETS) rig which employs rotating gas burners and air jet cooling stations and a stationary specimen fixture. A standard wedge shape specimen shown in Figure 47 was used.

Samples were taken from HPT vanes, LPT vanes and HPT inner bands at different areas of interest. Figure 48 shows the areas that were SETS tested in NNS components. The SETS data are shown in Table 18 and Figures 49, 50 and 51 and are compared to standard MA754. As expected, cracks first appeared in the samples containing areas of misorientation and high modulus, while most of the remaining samples were similar to or slightly better than conventional MA754.

TABLE 13

NNS HPT VANE TENSILE TEST RESULTS

SPEC #	TEST TEMP	TEST DIRECTION	FORGE TEMP °F	PREFORM DESIGN	UTS KSI	.2%YS KSI	.02%YS KSI	% EL	% RA	REMARKS
Conventional										
MA754	RT	Long	-	-	136.2	83.9	71.7	23.7	52.5	
8-H11L	RT	Long	1800	D1	140.3	86.0	73.5	24.0	58.5	Gage Failure
18-H24L	RT	Long	1800	D2	138.9	86.4	73.9	20.9	45.2	Gage Failure
22-H37L	RT	Long	1800	D3	139.2	85.9	74.1	18.3	29.1	Gage Failure
32-H40L	RT	Long	1750	D1	142.0	87.9	76.6	22.3	46.7	Gage Failure
Conventional										
MA754	1600	Long	-	-	35.3	30.4	20.9	23.4	59.1	Gage Failure
10-H1L	1600	Long	1800	D1	36.9	30.2	25.1	23.9	59.8	Gage Failure
17-H14L	1600	Long	1800	D2	36.8	33.5	25.9	26.6	57.9	Gage Failure
22-H27L	1600	Long	1800	D3	36.9	32.2	25.1	24.4	58.3	Gage Failure
36-H50L	1600	Long	1750	D1	38.2	33.2	27.1	33.6	63.8	Gage Failure
Conventional										
MA754	1800	Long	-	-	27.4	25.3	20.3	13.4	36.3	
10-H2L	1800	Long	1800	D1	29.4	26.4	20.6	19.0	56.3	Gage Failure
17-H15L	1800	Long	1800	D2	27.1	24.9	21.1	17.9	49.7	Gage Failure
22-H28L	1800	Long	1800	D3	31.2	26.6	21.1	24.1	62.8	Gage Failure
32-H41L	1800	Long	1750	D1	29.1	25.4	21.6	16.4	44.8	Gage Failure
Conventional										
MA754	2000	Long	-	-	21.9	20.9	17.2	9.7	22.4	Gage Failure
10-H3L	2000	Long	1800	D1	23.7	21.1	16.7	15.6	43.2	Gage Failure
17-H16L	2000	Long	1800	D2	22.1	21.1	17.3	13.3	39.5	Gage Failure
22-H29L	2000	Long	1800	D3	22.2	21.0	18.6	15.9	50.3	Gage Failure
32-H42L	2000	Long	1750	D1	25.2	23.8	19.3	19.1	51.3	Gage Failure
Conventional										
MA754	1800	Long Trans.	-	-	26.4	25.8	22.2	-	5.0	Gage Failure
10-H5T	1800	Trans.	1800	D1	25.2	23.4	18.6	2.5	3.8	Gage Failure
17-H18T	1800	Trans.	1800	D2	25.4	25.2	22.2	3.5	2.5	Gage Failure
22-H31T	1800	Trans.	1800	D3	24.7	22.9	19.6	3.4	3.8	Gage Failure
32-H44T	1800	Trans.	1750	D1	26.6	25.2	20.6	3.2	1.3	Gage Failure

TABLE 13 (Continued)

NNS HPT VANE TENSILE TEST RESULTS

SPEC #	TEST TEMP	TEST DIRECTION	FORGE TEMP °F	PREFORM DESIGN	UTS KSI	.2%YS KSI	.02%YS KSI	% EL	% RA	REMARKS
Conventional MA754	2000	Long Trans.	-	-	20.5	20.2	16.6	-	1.6	Gage Failure
10-H6T	2000	Trans.	1800	D1	16.6	-	15.1	-	-	Radius Failure
17-H19T	2000	Trans.	1800	D2	17.6	-	-	-	-	Near Radius
22-H32T	2000	Trans.	1800	D3	19.9	19.9	18.2	-	-	Near Radius
32-H45T	2000	Trans.	1750	D1	14.7	-	13.8	1.7	1.5	Gage Failure

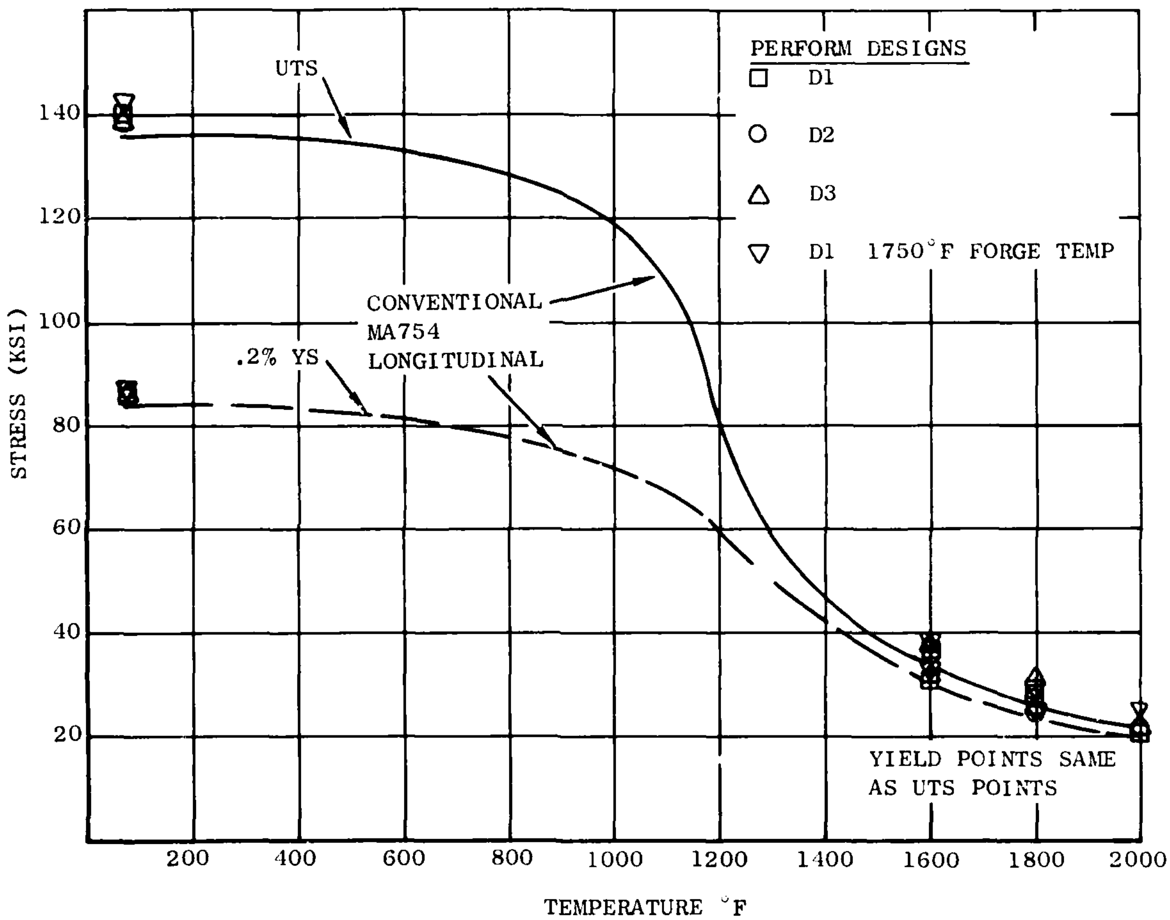


Figure 43-A NNS HPT Vane Longitudinal Tensile Results

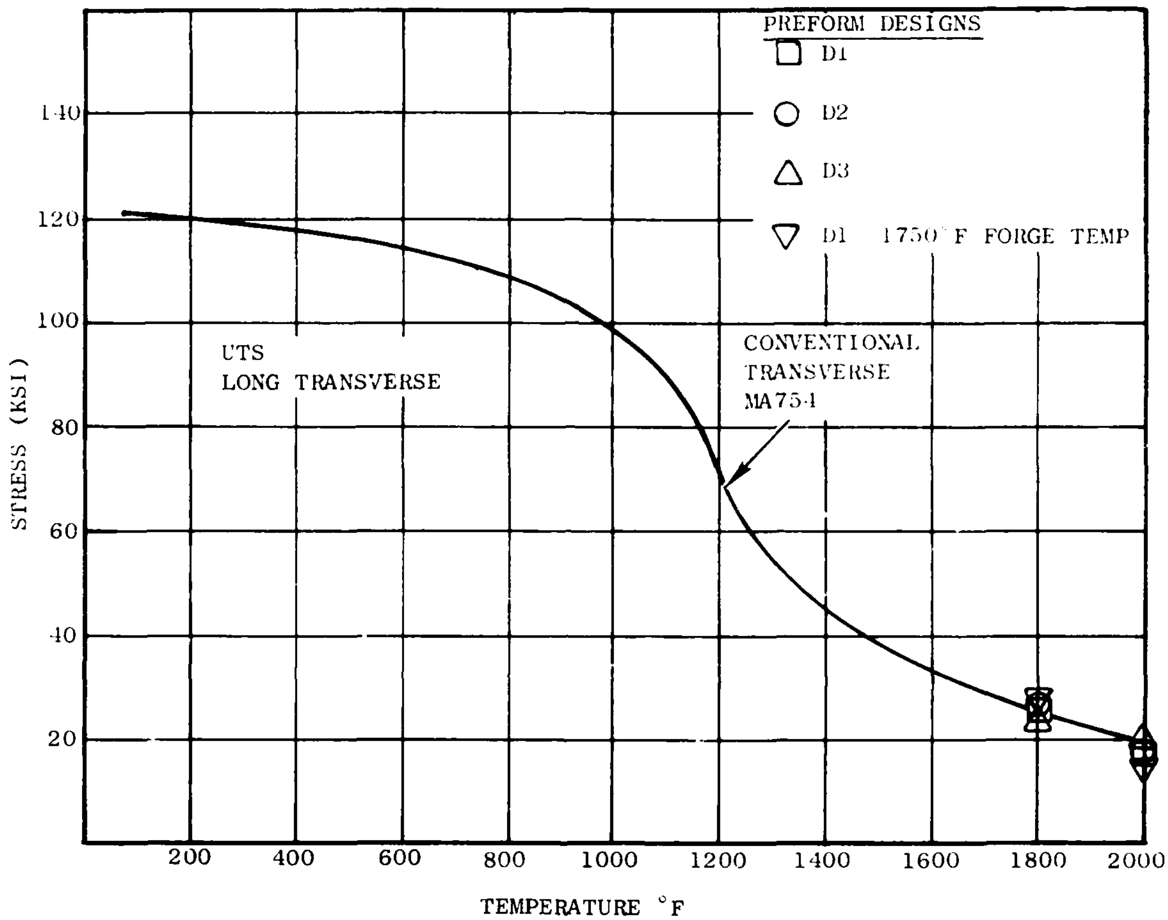


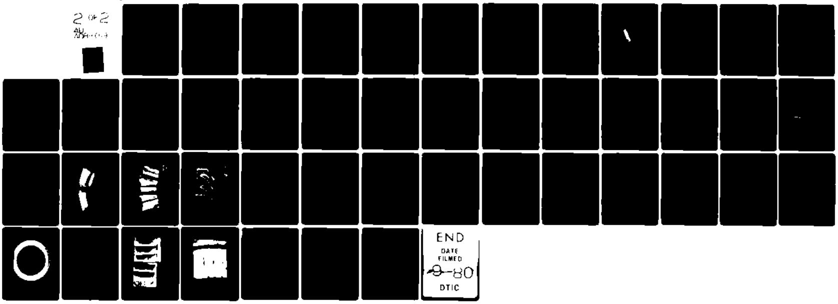
Figure 43-B. NNS HPT Vane Transverse Tensile Results

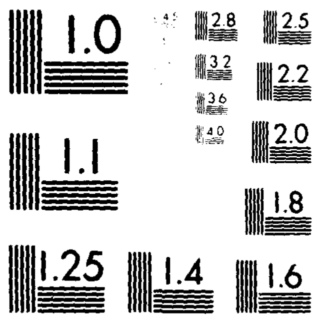
TABLE 14

TENSILE TEST RESULTS NNS HPT BANDS & LPT VANES

SPEC #	TEST TEMP	TEST DIRECTION	CONFIGURATION	UTS KSI	.2%Y.S. KSI	.02%Y.S. KSI	% EL	% RA	REMARKS
Conv MA754	RT	Long	-	136.2	83.9	71.7	23.7	52.5	Gage
13-B1L	RT	Long	Inner Band	140.7	80.4	76.4	22.7	57.3	Gage
17-LP7L	RT	Long	LPT Vane	140.5	83.9	69.8	22.7	53.8	Gage
Conv MA754	1600	Long	-	35.3	30.4	20.9	23.4	59.1	Gage
13-B2L	1600	Long	Inner Band	34.6	29.9	21.9	24.1	58.7	Gage
17-LP8L	1600	Long	LPT Vane	36.1	16.3	13.7	29.4	59.7	Gage
Conv MA754	1800	Long	-	27.4	25.3	20.3	13.4	36.3	
13-B3L	1800	Long	Inner Band	28.1	25.9	23.1	16.3	48.7	Gage
10-LP3L	1800	Long	LPT Vane	27.9	26.4	24.4	20.0	52.3	Gage
22-L-5L	1800	Long	LPT Vane	27.0	24.5	20.0	21.3	49.0	Gage 1850 Roll Temp. Coarse G.S.
Conv MA754	2000	Long	-	20.5	20.2	16.6	-	1.6	Gage
13-B4L	2000	Long	Inner Band	23.5	22.0	19.6	14.7	39.8	Gage
10-LP4L	2000	Long	LPT Vane	23.3	22.3	20.4	12.4	27.1	Gage
22-LP6L	2000	Long	LPT Vane	29.4	28.9	25.0	-	11.7	Gage 1850 Roll Temp. Coarse G.S.
Conv MA754	1800	Long Trans	-	26.4	25.8	22.2	-	5.0	Gage
13-B5T	1800	Long Trans	Inner Band	23.9	18.4	15.9	3.9	3.5	Gage Near Radius
LP13T	1800	Trans	LPT Vane	27.1	26.6	26.2	11.3	8.9	Gage
Conv MA754	2000	Long Trans	-	20.5	20.2	16.6	-	1.6	Gage
13-B6T	2000	Long Trans	Inner Band	19.9	19.8	17.0	3.0	1.5	Gage Near Radius
LP2T	2000	Trans	LPT Vane	20.5	20.5	20.3	15.0	6.4	Gage

AD-A088 019 GENERAL ELECTRIC CO CINCINNATI OH AIRCRAFT ENGINE GROUP F/G 21/5
LOW COST PROCESS FOR MANUFACTURE OF OXIDE DISPERSION STRENGTHEN--ETC(U)
DEC 79 J A STAHL, R J PERKINS, P G BAILEY F33615-76-C-5235
UNCLASSIFIED AFML-TR-79-4163 NL





MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS 1963 A

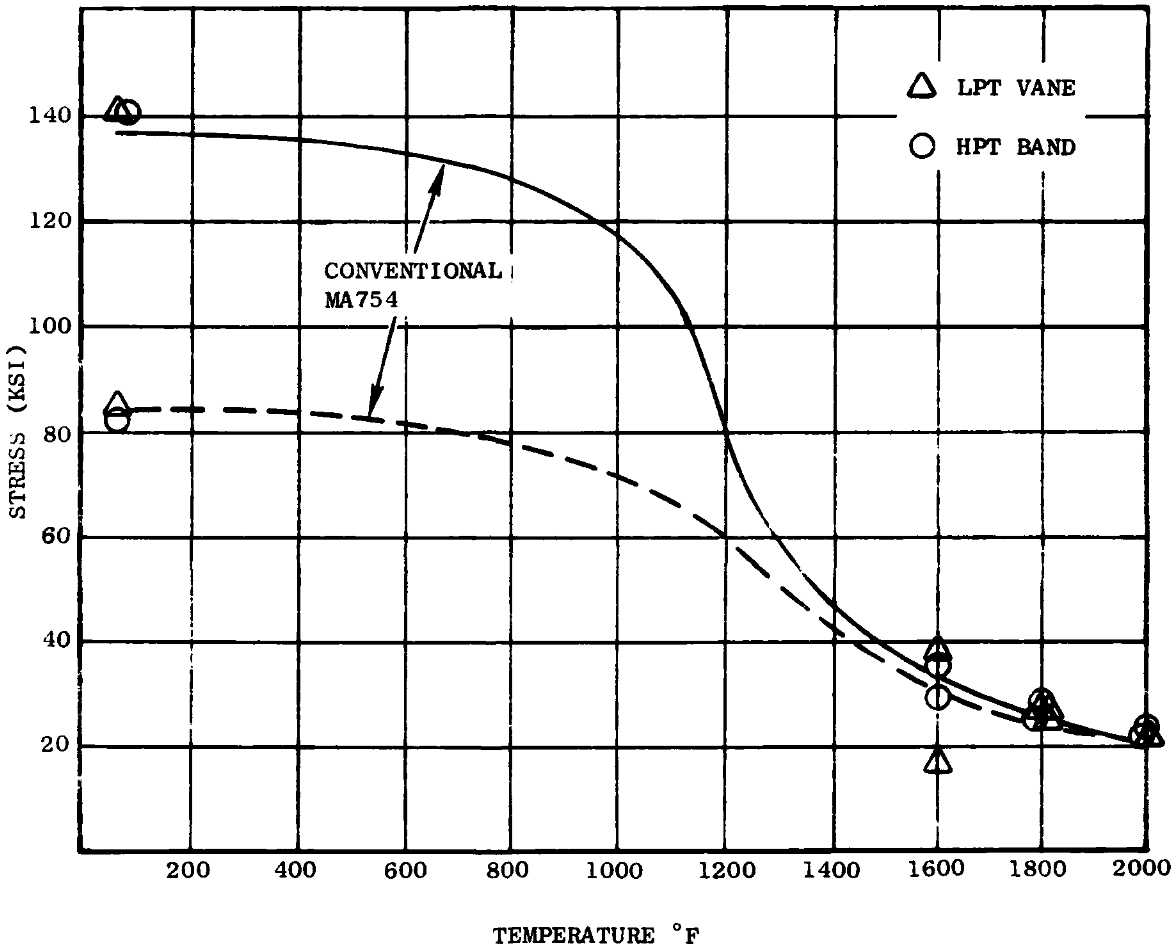


Figure 44-A. NNS LPT Vane and HPT Band Longitudinal Tensile Results

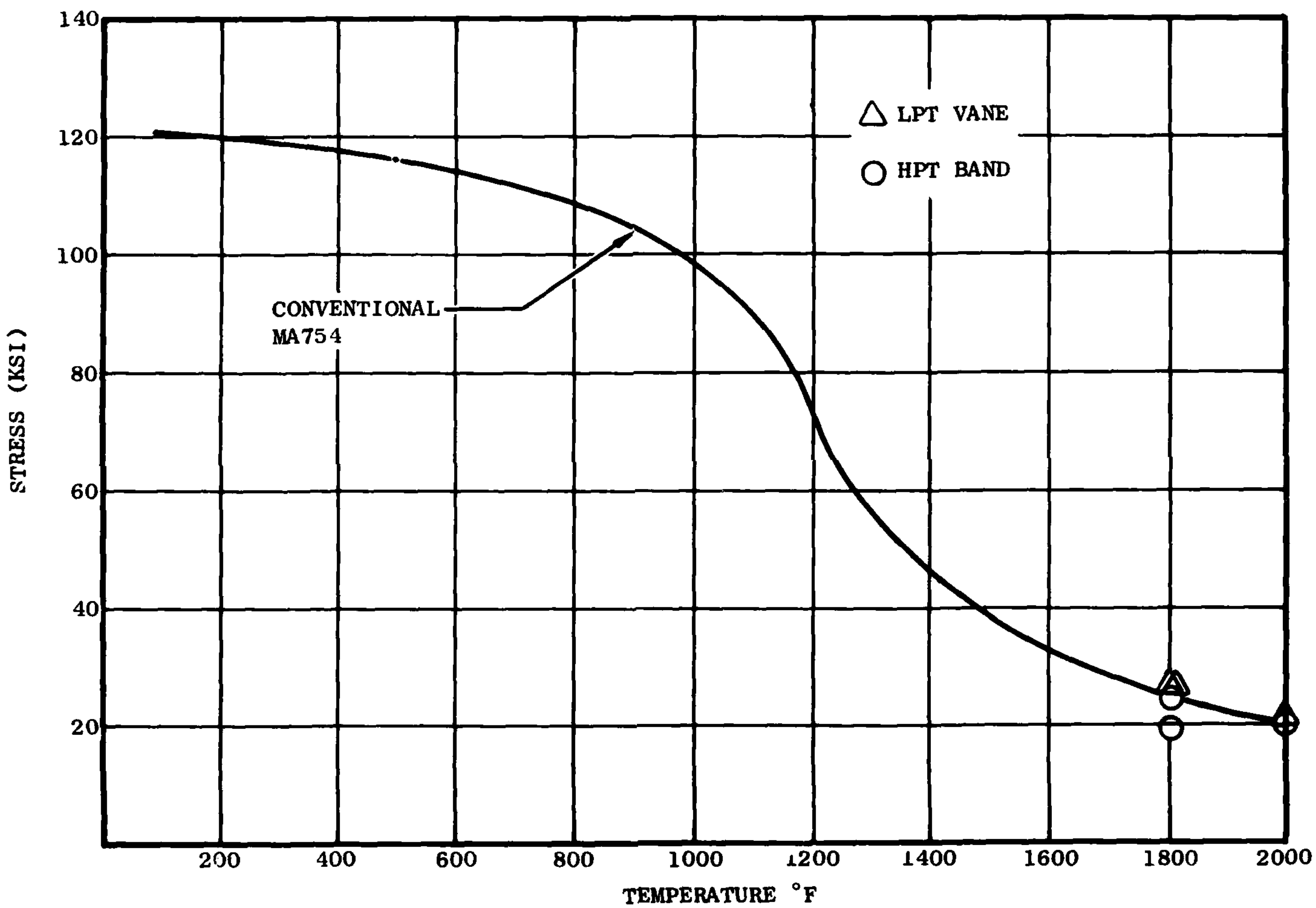


Figure 44-B. NNS LPT Vane and HPT Band Transverse Tensile Results

TABLE 15

NEAR NET SHAPE HPT VANES STRESS RUPTURE RESULTS

SPEC #	TEST TEMP °F	TEST DIRECTION	STRESS KSI	LIFE HRS	% EL	% RA	REMARKS	PREFORM DESIGN
H12T	1800	Trans	7.0	191.8	-	-	Step Load	D1
			↓ 8.0	71.6	-	-	Step Load	D1
			↓ 9.0	45.6	-	-	Thread Fail	D1
			TOT	279.0				
H25T	1800	Trans	9.0	17.2	-	-	Gage Fail	D2
H38T	1800	Trans	8.5	215	-	-	Step Load	D3
			↓ 9.0	72.6	-	-	Step Load	D3
			↓ 10.0	113.1	-	-	Stop Test	D3
			TOT	400.7				
H51T	1800	Trans	8.5	69.2	2.1	.7	Gage Fail Near Radius	D1 1750 Forge Temp.
H13T	2000	Trans	4.0	171.0	-	-	Step Load	D1
			↓ 5.0	45.8	-	2.9	Gage Fail Near Radius	D1
			TOT	216.8				
H26T	2000	Trans	5.5	66.7	-	-	3 Piece Fail	D2
H39T	2000	Trans	6.0	18.1	2.1	-	Gage Fail	D3
H52T	2000	Trans	5.5	11.9	2.1	-	Gage Fail	D1 1750 Forge Temp.
32-H43L	1600	Long	27.0	254.8	2.8	2.5	Disc	D1 1750 Forge Temp.
10-H4L	1600	Long	27.0	87.6	9.1	24.7	Gage Fail	D1
17-H17L	1600	Long	27.0	20.2	13.5	45.8	Gage Fail	D2
22-H30L	1600	Long	27.0	17.9	12.8	26.8	Gage Fail	D3
8-H7L	1800	Long	21.0	228.6	0	1.3	Disc	D1

TABLE 15 (Continued)

NEAR NET SHAPE HPT VANES STRESS RUPTURE RESULTS

SPEC #	TEST TEMP °F	TEST DIRECTION	STRESS KSI	LIFE HRS	% EL	% RA	REMARKS	PREFORM DESIGN
8-H8L	1800	Long	22.0	170.5	9.0	22.5	Gage Fail	D1
18-H20L	1800	Long	22.0	32.7	9.0	19.1	Gage Fail	D2
30-H33L	1800	Long	20.0	91.0	-	-	Disc	D3
30-H34L	1800	Long	21.0	255.8	.6	1.3	Disc	D3
36-H46L	1800	Long	21.0	378.0	.96	1.3	Disc	D1 1750 Forge Temp.
H35L	2000	Long	14.0	192				
			15.0	96				
			16.0	90				
			TOT	378	.5		Disc	D3
H48L	2000	Long	14.0	214				
			15.0	96				
			16.0	89.8				
			TOT	399.8	.97		Disc	D1
30-H36L	2000	Long	15.0	257.0	.7		Disc	
36-H49L	2000	Long	16.0	126.8	15.9	19.8	Gage Fail	D1 1750 Forge Temp.
8-H9L	2000	Long	16.0	187.3				
			17.0	117.8	.69	1.9	Disc	D1
			TOT	305.1				
8-H10L	2000	Long	18.0	77.8	9.1	14.6	Gage Fail	D1
H22L	2000	Long	18.0	38.5	11.0	22.5	Gage Fail	D2

TABLE 16

NNS LPT VANE STRESS RUPTURE RESULTS

SPEC #	TEST TEMP °F	TEST DIRECTION	STRESS KSI	LIFE HRS	LARSEN MILLER PARAMETER	% EL	% RA	REMARKS	SPEC LOCATION
12-LP19L	1600	LPT Long	27.0	24.7	54.4	14.5	28.9	Gage Failure	Bend
2-LP9L	1800	LPT Long	21.0	72.0	60.7	8.9	13.4	Gage Failure	Bend
2-LP10L	1800	LPT Long	21.0	49.6	60.4	10.6	31.1	Gage Failure	Bend
2-LP11L	2000	LPT Long	17.0	74.3	66.0	10.3	27.0	Gage Failure	Bend
2-LP126	2000	LPT Long	17.0	71.4	66.0	9.0	12.2	Gage Failure	Bend
12-LP17L	1800	LPT Long	22.0	58.6	60.5	7.6	16.6	Gage Failure	Straight
12-LP18L	2000	LPT Long	17.0	112.2	66.6	8.7	16.9	Gage Failure	Straight
17-LP15T	2000	LPT Trans	5.5	69.1	1.0	1.7	0	Gage Failure	Bend

TABLE 17

NNS BANDS STRESS RUPTURE RESULTS

SPEC #	TEST TEMP °F	TEST DIRECTION	STRESS KSI	LIFE HRS	% EL	% RA	REMARKS	LARSEN MILLER
B11L	1600	Long	25	145.2				
			26	95.2				
			27	89.4				
			TOT	229.8	1.4	1.9	Disc	55.9 →
11B12L	1800	Long	20	495.7	5.5	1.3	Disc	62.6 →
11B13L	1800	Long	21	303.8	2.5	-	Disc	62.2 →
B14L	2000	Long	14	280	.27	-	Disc	67.6 →
11B15L	2000	Long	16	306.8	.27	-	Disc	67.7 →
11B7T	1800	Trans	8	296.1	-	-	Disc	
11B8T	1800	Trans	10	232.3	.14	-	Disc	60.6 →
11B10T	2000	Trans	4.5	222	.27	-	Disc	67.3 →
11B9T	2000	Trans	5.5	259.4	.41	-	Disc	66.1 →

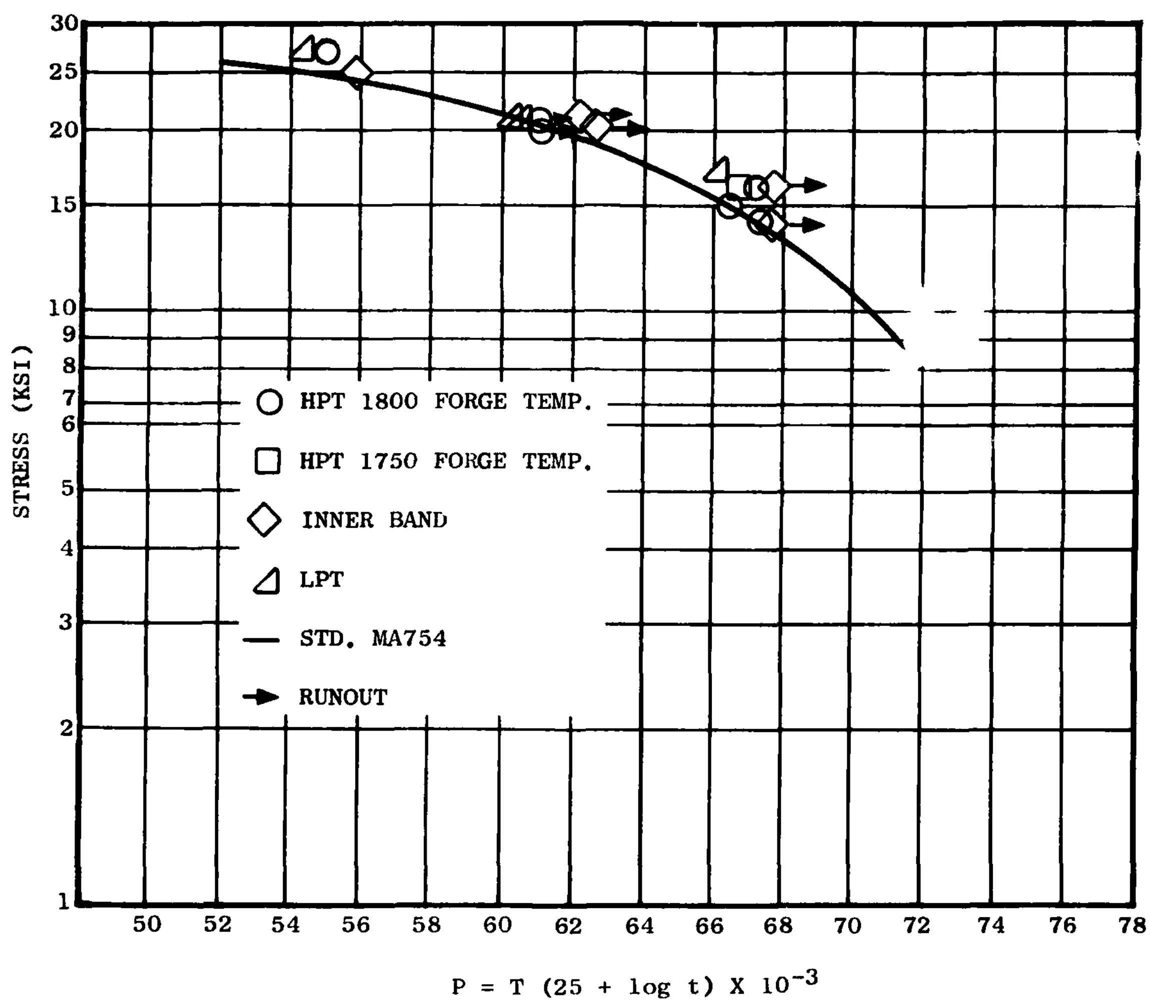


Figure 45. Near-Net Shape Longitudinal Stress Rupture Results

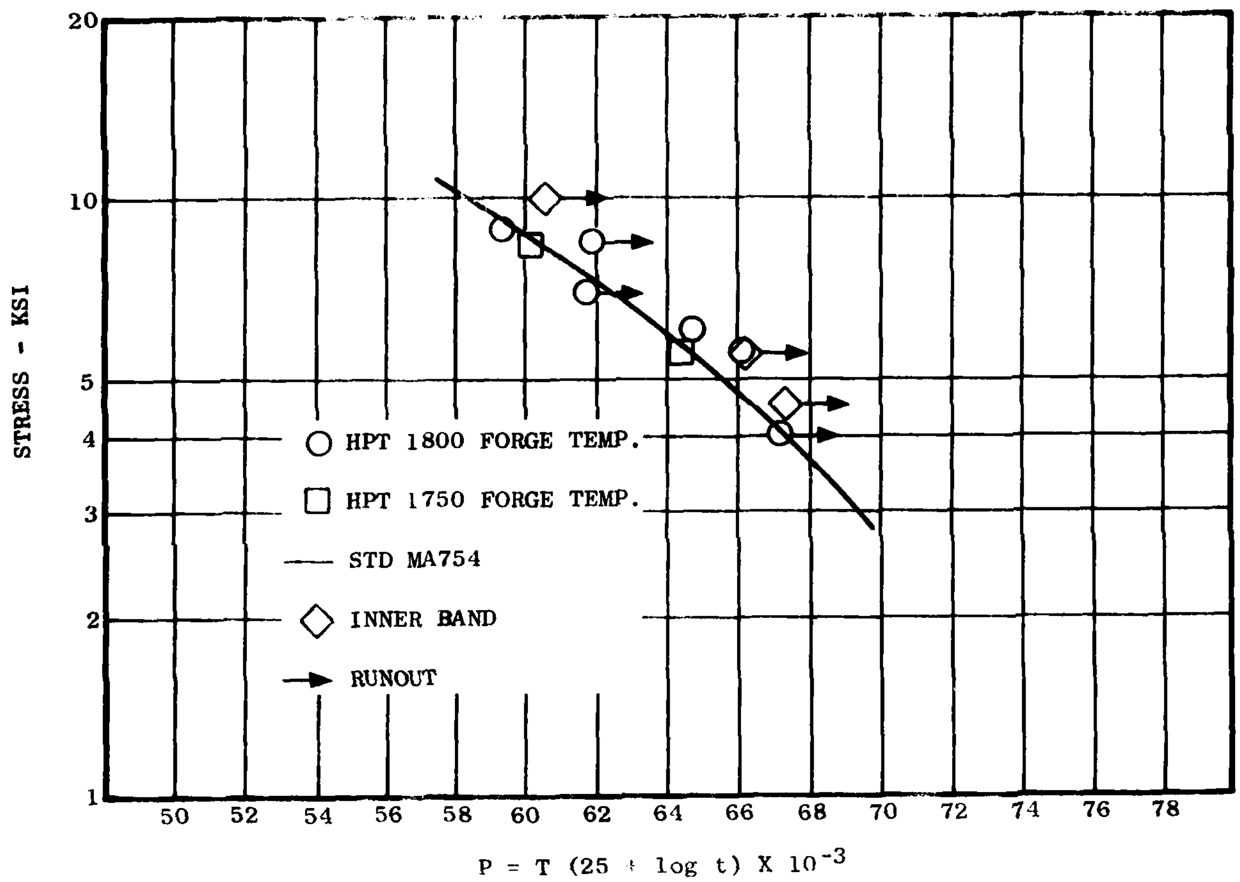
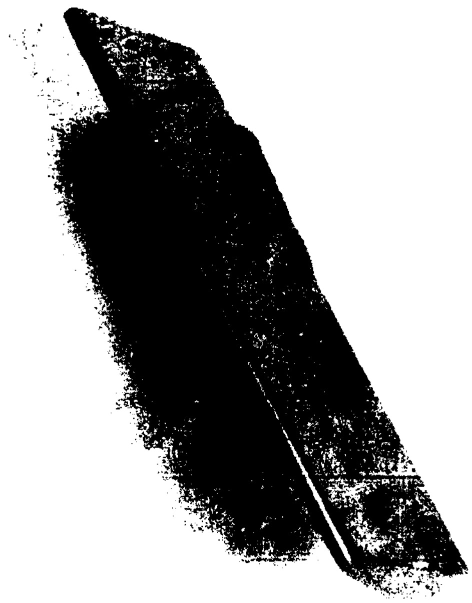


Figure 46. Near-Net Shape Transverse Stress Rupture Results



2X

Figure 47. Near-Net Shape MA754 Thermal Fatigue Specimen

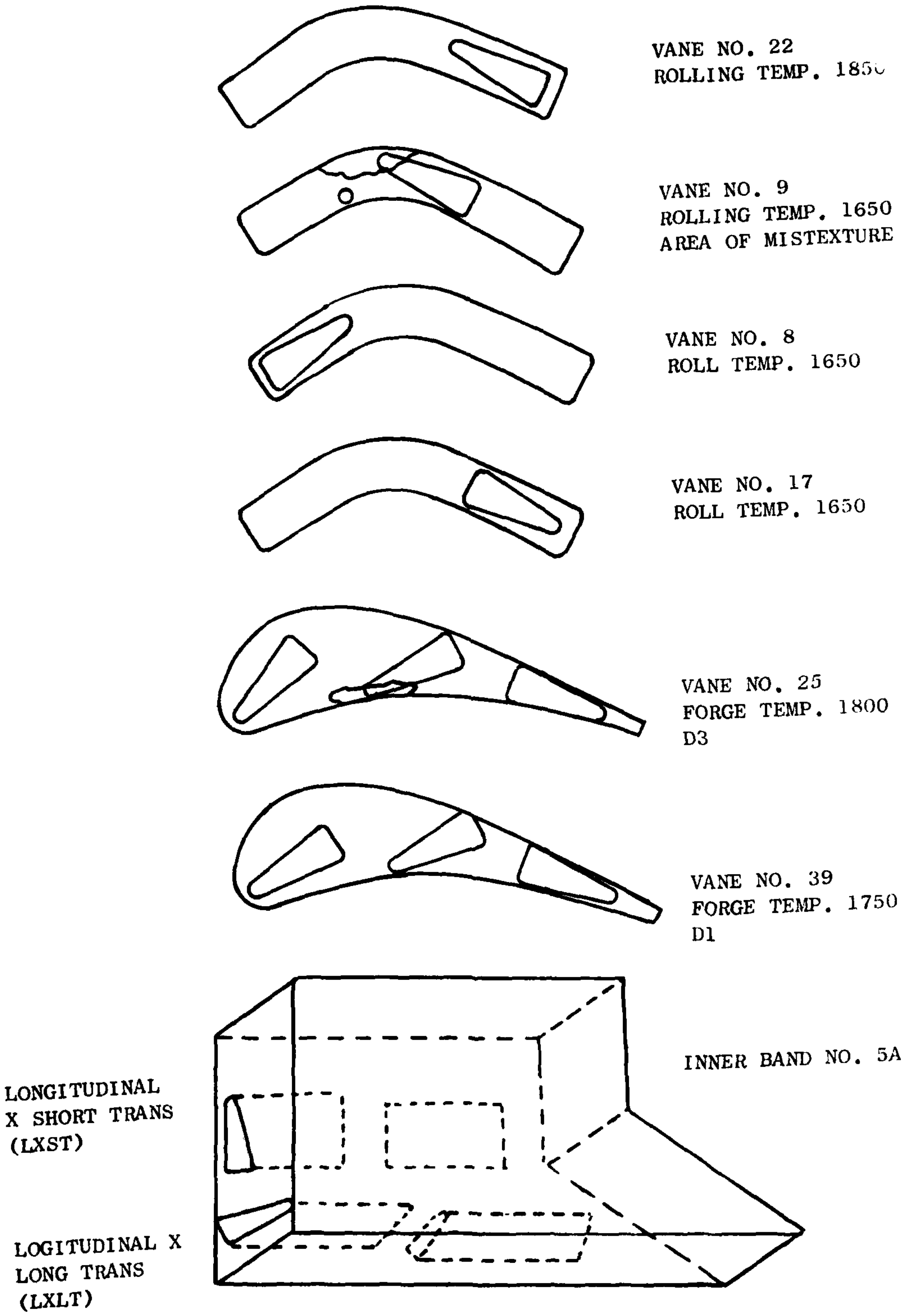


Figure 48. SETS Specimen Locations

TABLE 18

NNS SIMULATED ENGINE THERMAL SHOCK (SETS) RESULTS CRACK SEVERITY INDEX RATINGS

Index No.	Degree of Cracking
0	No cracking or surface deterioration
1	Pits at leading edge - not discernible as cracks
2	One to three cracks which do not traverse the leading edge arc
3	Four or more cracks which do not traverse the leading edge arc
4	One to three cracks which traverse the leading edge arc
5	Four or more cracks which traverse the leading edge arc
6	One to three cracks which extend past the leading edge arc
7	Four or more cracks which extend pas the leading edge arc
8	One to three cracks which extend past the leading edge arc by at least 3/32 inch
9	Four or more cracks which extend past the leading edge arc by at at least 3/32 inch
10	One or more cracks which extend past the leading edge arc by at least 3/16 inch

SPEC NO / CYCLES	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
100																
200														2		
300														2+		
500										1			2	4		
650				2						1		1	2	6	1	1
1000			2	3	2			2		1	1	2	6	6	1+	1+
1150	1	2	2	4	2	2	1	2		1	1	2	6	6	1+	1+
1300	1	2	2	4	2	2	1	2	1	1+	1+	2	6+	7	2	3
1750	1	4	2	6	4	4	3	4	1	1+	1+	2	6+	7	2	3
1800	1	4	2	6	4	4	3	4	1+	1+	2	2	8	7	4	3
2050	2	6	4	6+	6	6	6	6	1+	1+	2	2	8	7	4	3
2300	2	6	4	6+	6	6	6	6	4	2	4	2	8+	7	6	3+
2800	2	6	4	6+	6	6	6	6	6	2	6	4	8+	7+	6	6

TABLE 18 (Continued)

NNS SIMULATED ENGINE THERMAL SHOCK (SETS) RESULTS CRACK SEVERITY INDEX RATINGS

SPEC NO Cycles	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
3000	2	6	6	7	6+	7	7	6	6	2	6	4	8+	7+	6	6
4000	6	6	6+	7	7	7	7	6	6	3	6	6	9	8	6+	7

SPEC IDENTIFICATION
(SEE FIGURE 48 FOR SPECIMEN ORIENTATION)

SPEC NO	CONFIGURATION	SPEC NO	CONFIGURATION
1	LPT Vane	9	HPT Band
2	LPT Vane	10	HPT Band
3	HPT 1800°F Forge Temp	11	HPT Band
4	HPT 1800°F Forge Temp	12	HPT Band
5	HPT 1800°F Forge Temp	13	LPT Vane 1850°F Roll Temp
6	HPT 1750°F Forge Temp	14	LPT Vane Mistextured Area
7	HPT 1750°F Forge Temp	15	STD MA754 Bar
8	HPT 1750°F Forge Temp	16	STD MA754 Bar

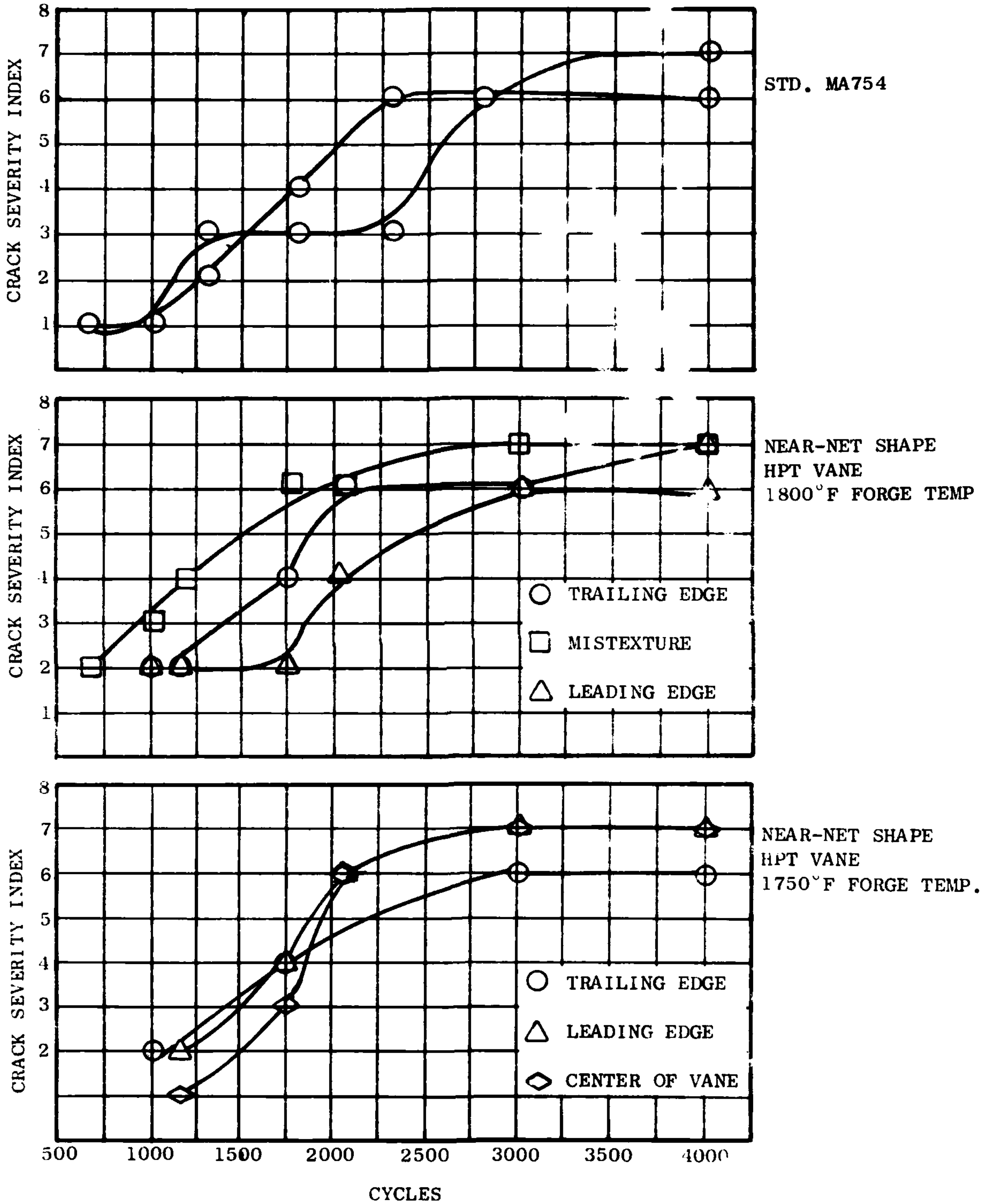


Figure 49. HPT Vane SETS Results

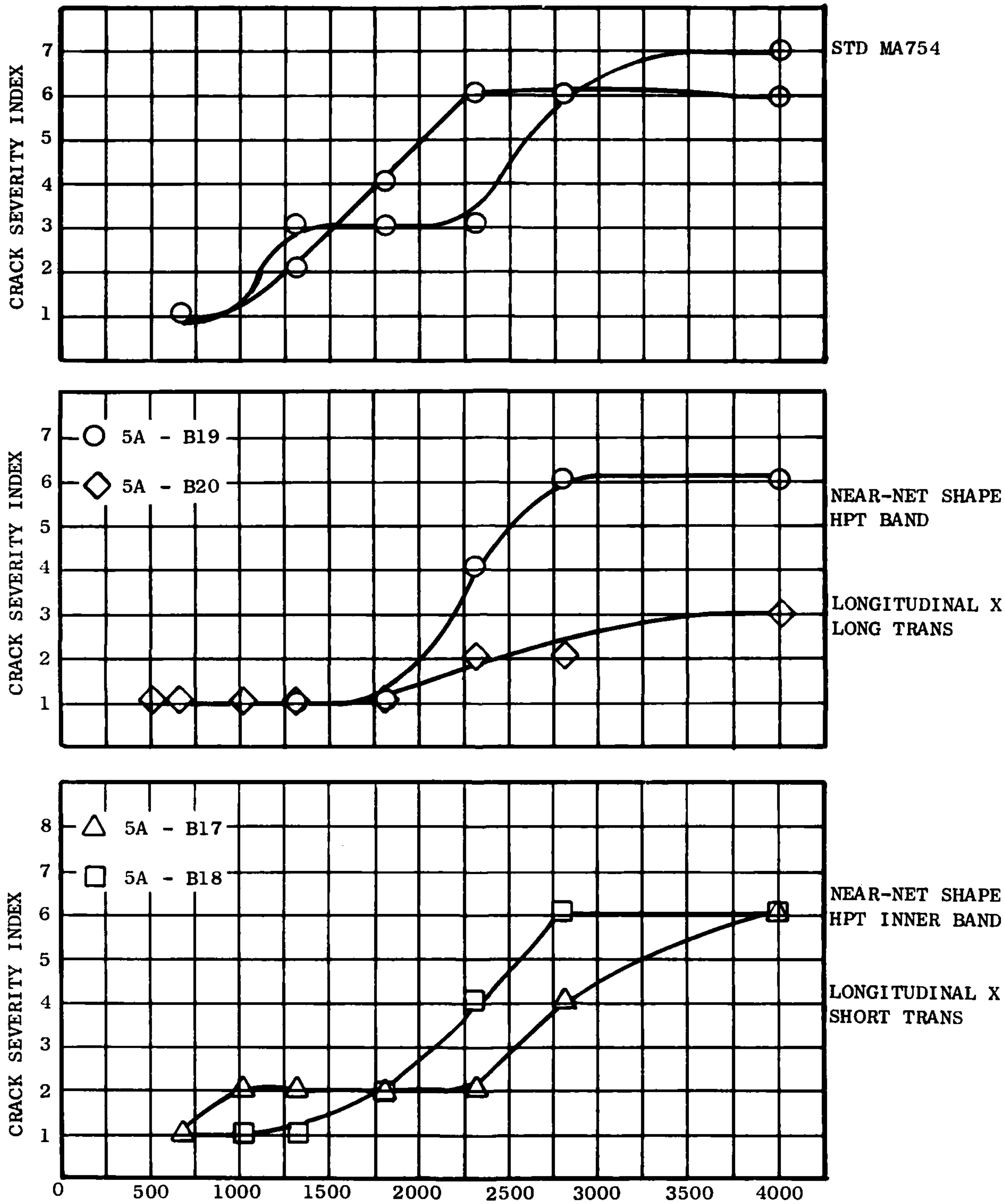


Figure 50. HPT Band SETS Results

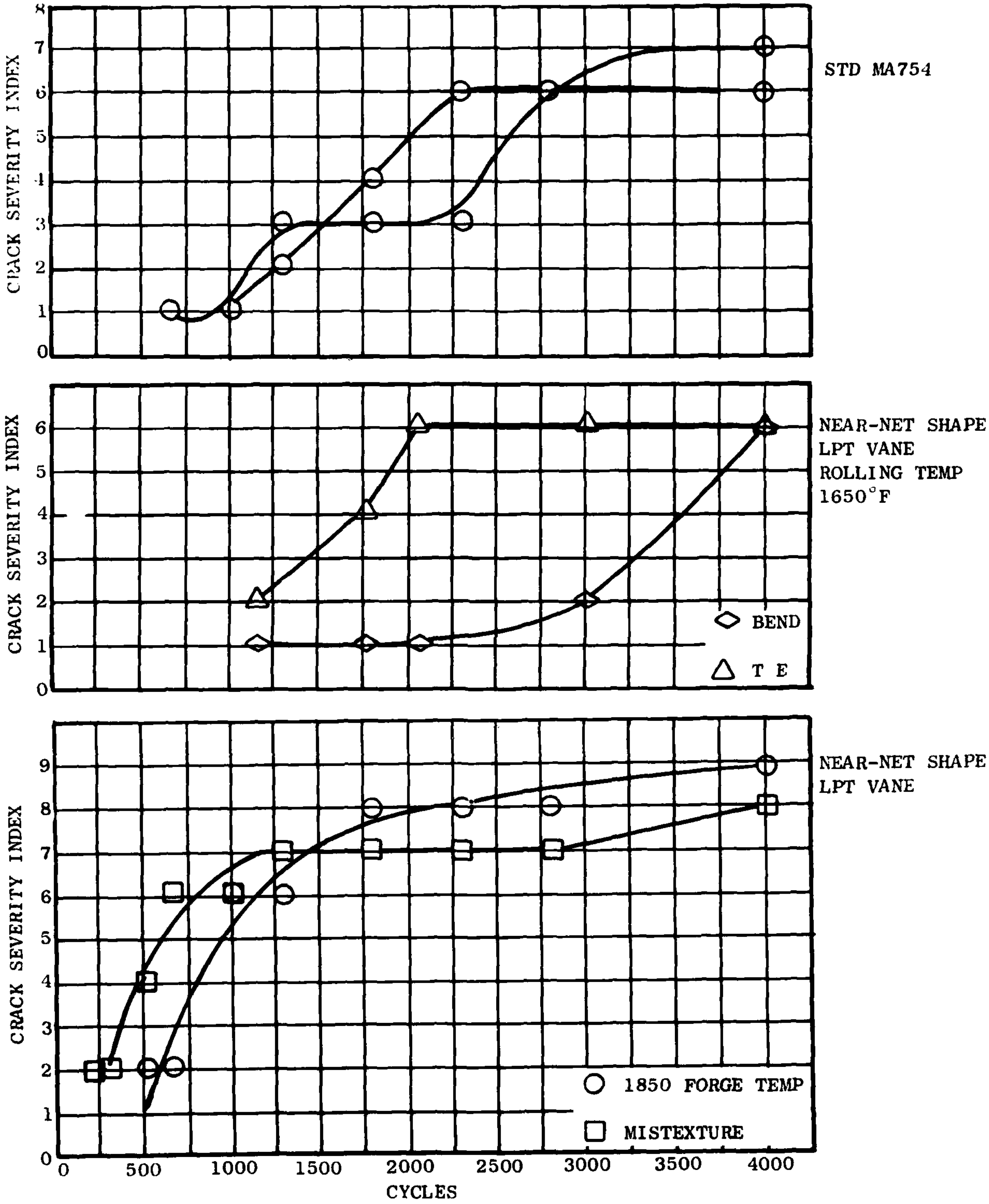


Figure 51. LPT Vane SETS Results

Dynamic Modulus

Dynamic modulus of elasticity determinations of MA754 NNS components were conducted to establish the effects of transverse strain caused by secondary working and recrystallization heat treatment. ODS alloys are highly processed in a single direction to achieve the (001) low modulus longitudinal texture and have a low tolerance for lateral and tangential material flow. Relatively small strains in a direction other than longitudinal have been shown to promote non-desirable crystallographic textures and higher modulus material than tolerable for turbine vane application. Six specimens were prepared from different areas of the NNS components. Figure 52 shows the component and location of the modulus specimens. Samples were tested from RT through 2000°F as shown in Figure 53. The results are shown in Figures 54 through 59. The specimen taken from a NNS LPT vane rolled at 1850°F had a dynamic modulus greater than the 25 X 10^6 PSI maximum permitted in the specification. A Laue diffraction test showed this sample to have a longitudinal texture 35° to (001) and 20° to (111) direction. The remaining five specimens were well within the required range.

The dynamic modulus of elasticity is calculated by the following equation:

$$E = .0041627 \; \frac{WL^3}{D^4 f} \, ^2 \; T$$

E = Modulus in PSI

W = Weight in pounds

L = Length in inches

D = Diameter in inches

f = Frequency in cycles per second

T = D/L Correction Factor

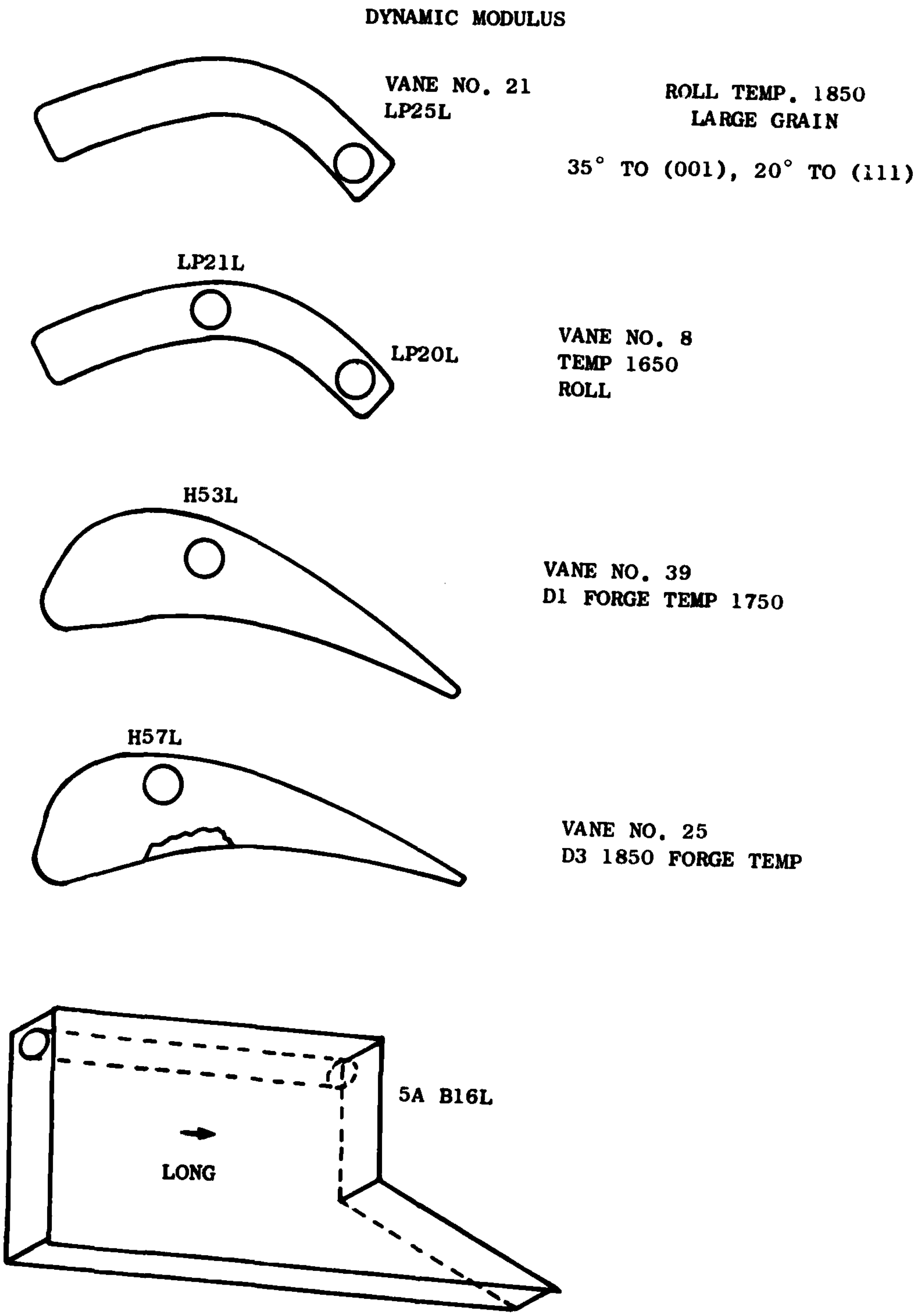


Figure 52. Dynamic Modulus Specimen Locations

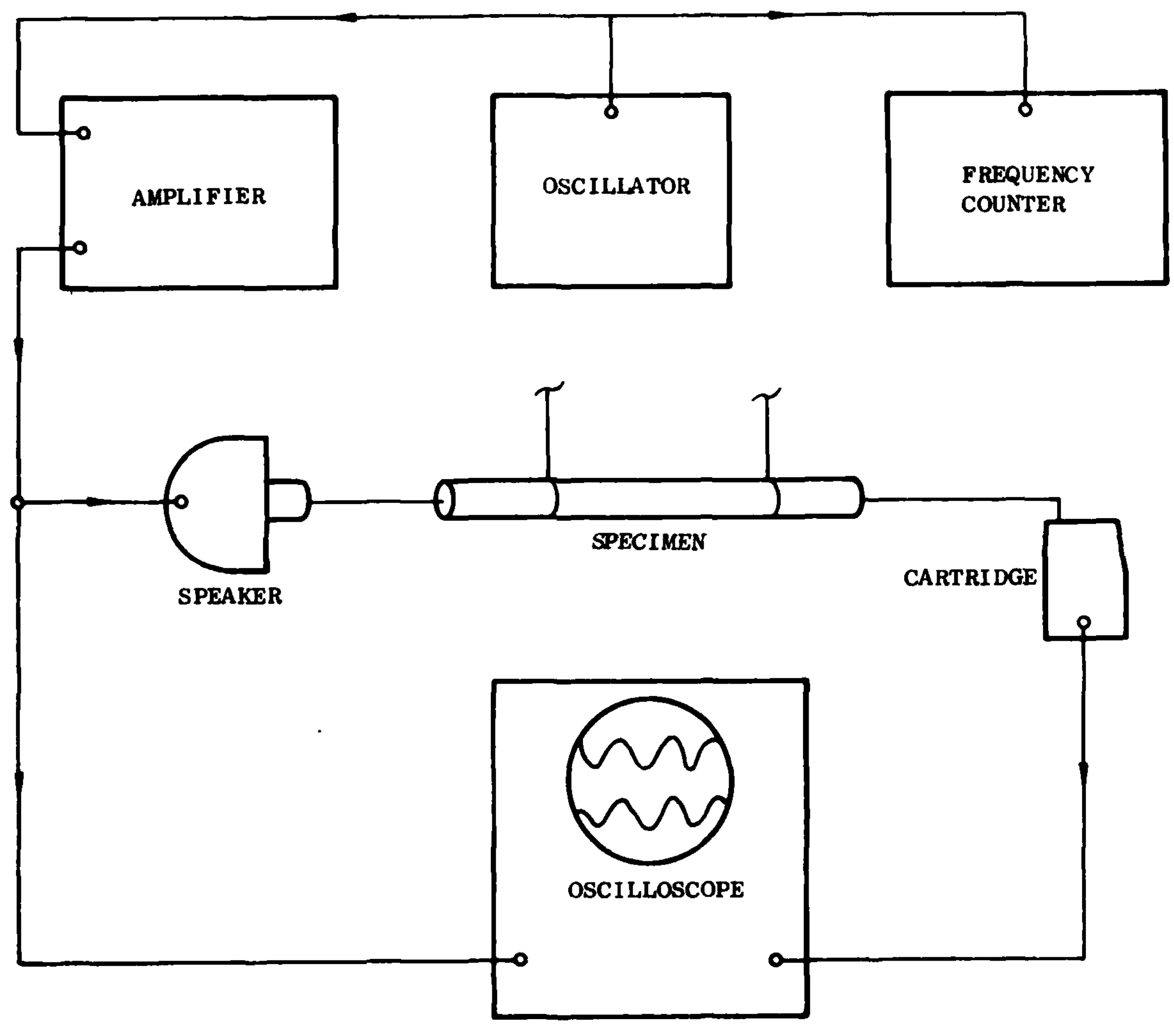


Figure 53. Dynamic Modulus Determination Technique

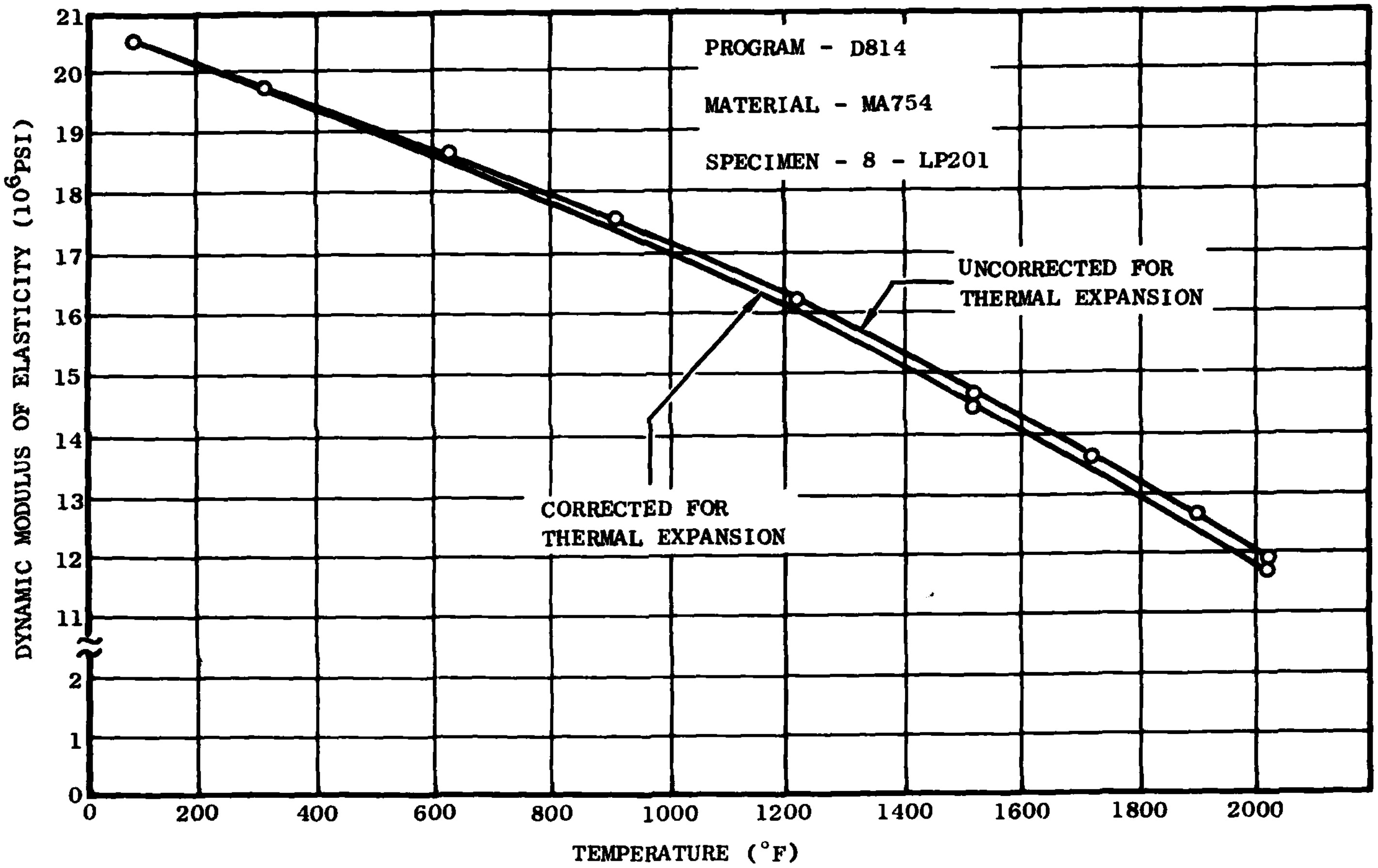


Figure 54. MA754 Specimen 8-LP20L Dynamic Modulus

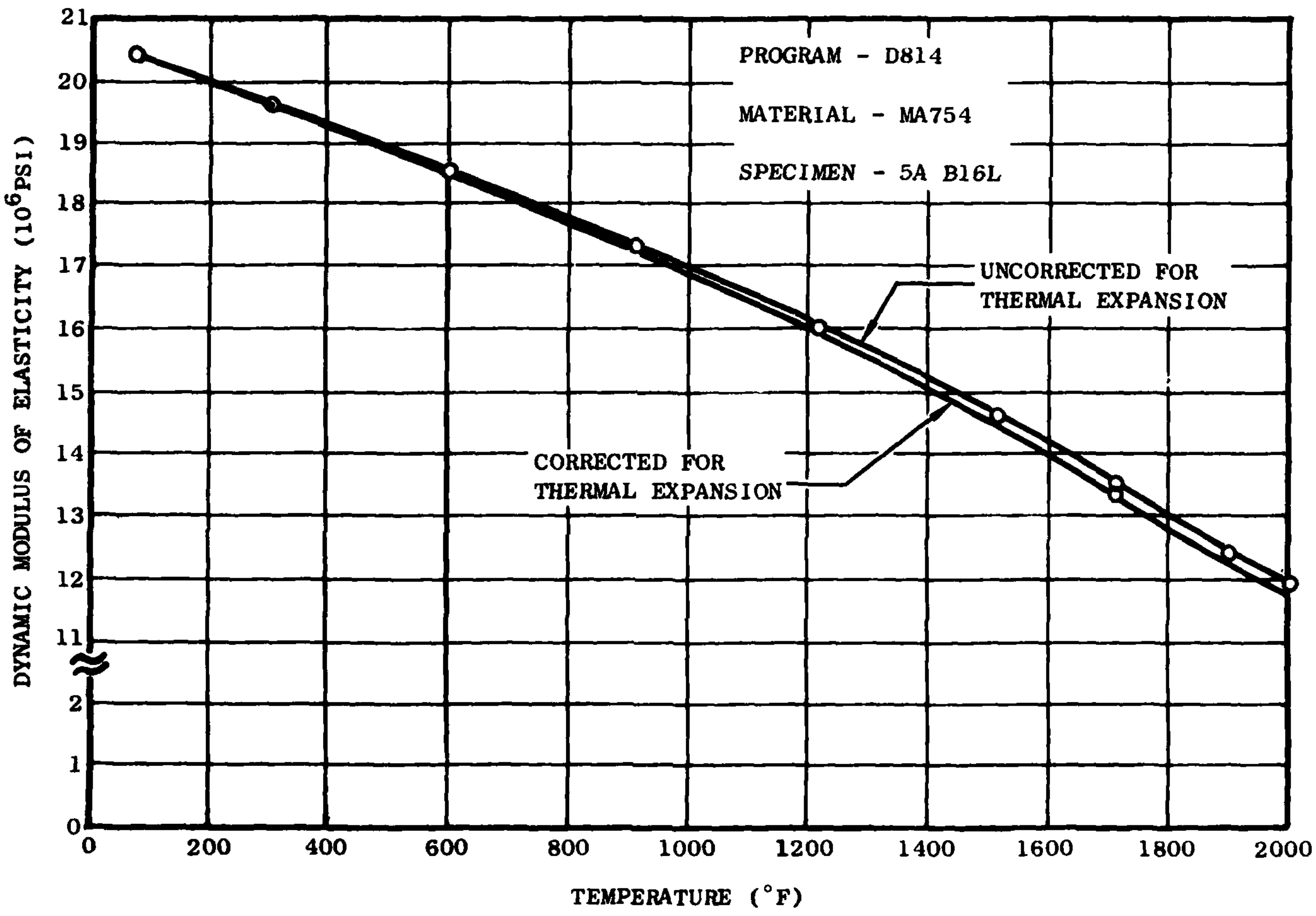


Figure 55. MA754 Specimen 5A-B16L Dynamic Modulus

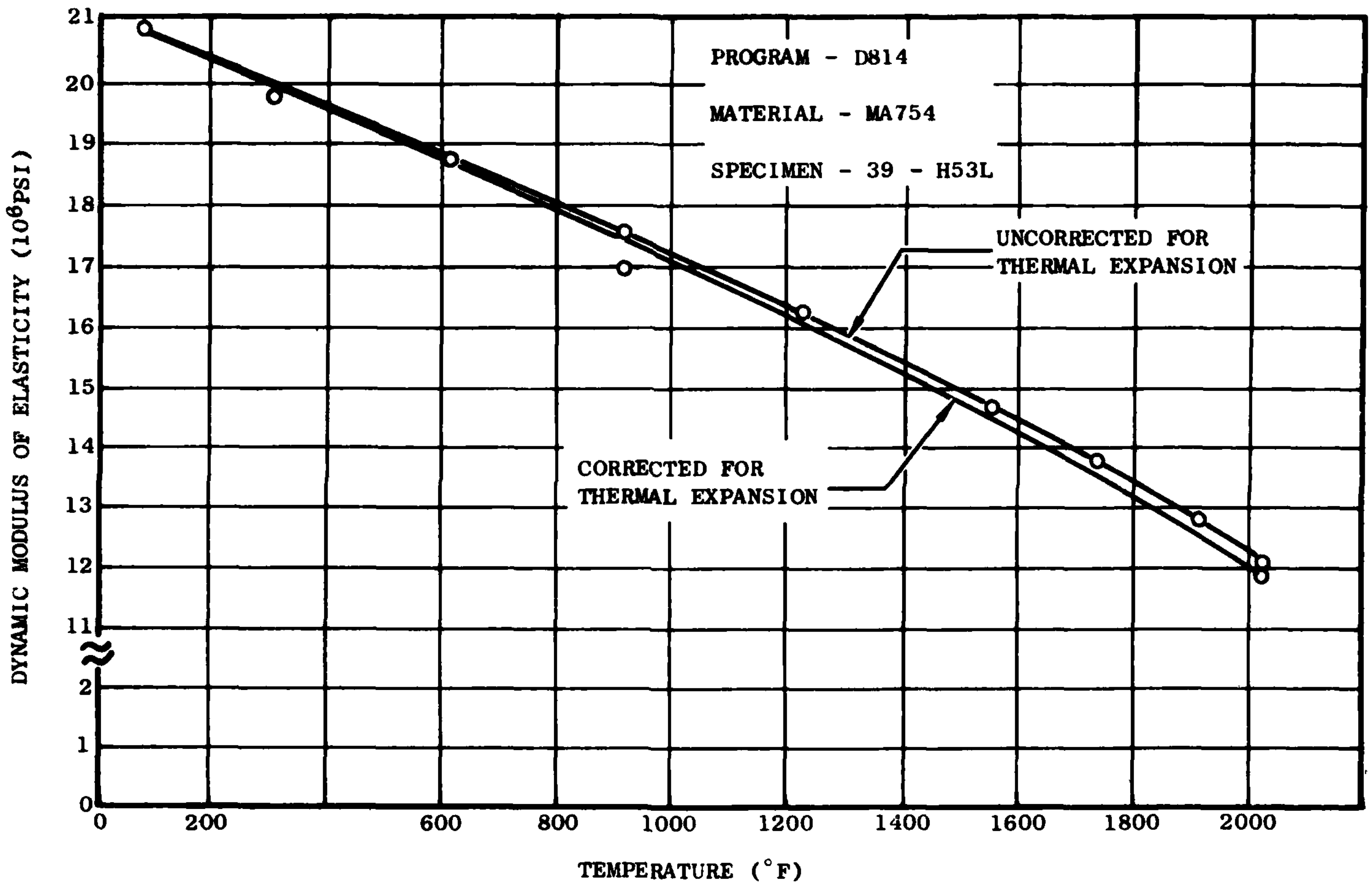


Figure 56. MA754 Specimen 39-H53L Dynamic Modulus

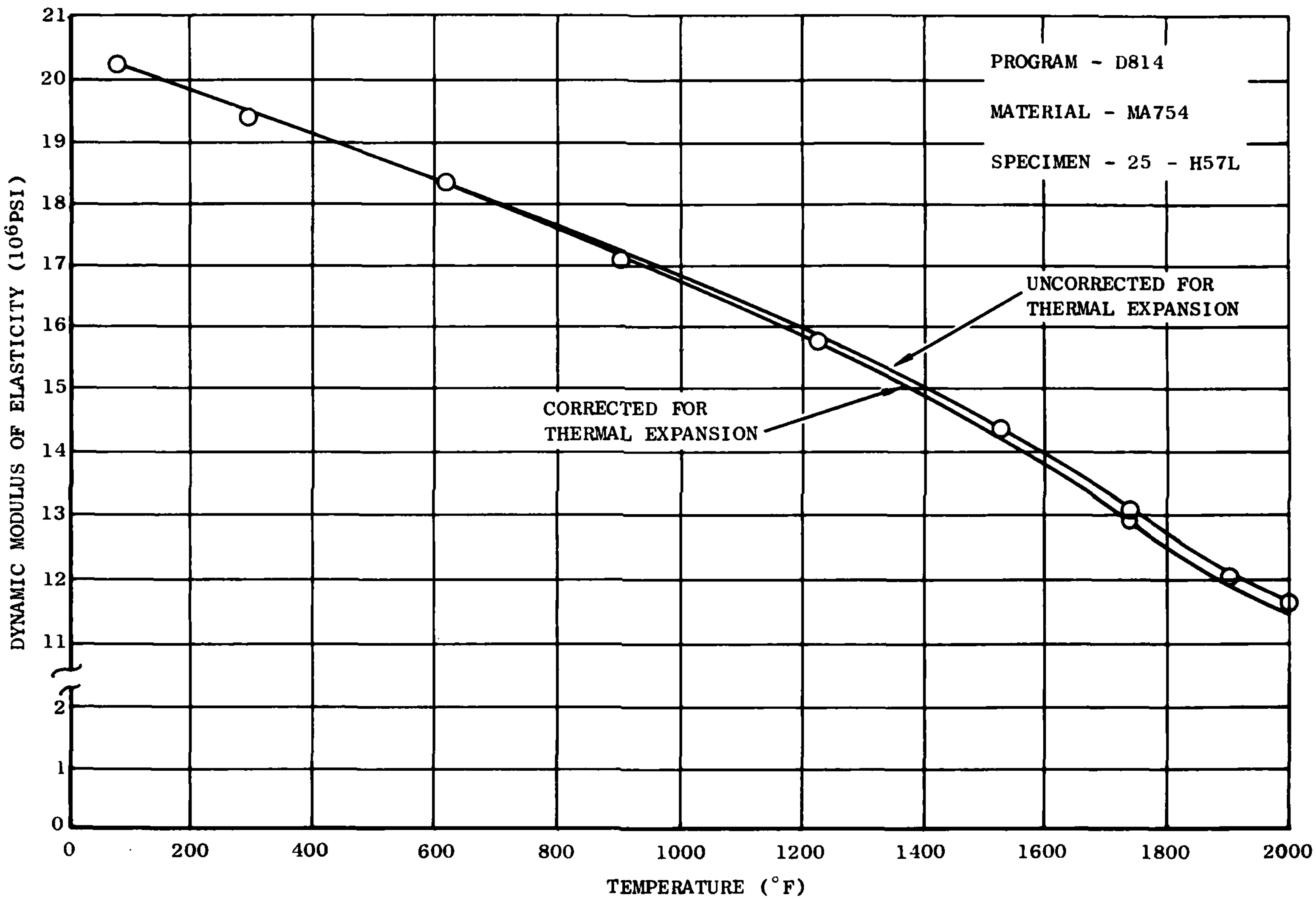


Figure 57. MA754 Specimen 25-H57L Dynamic Modulus

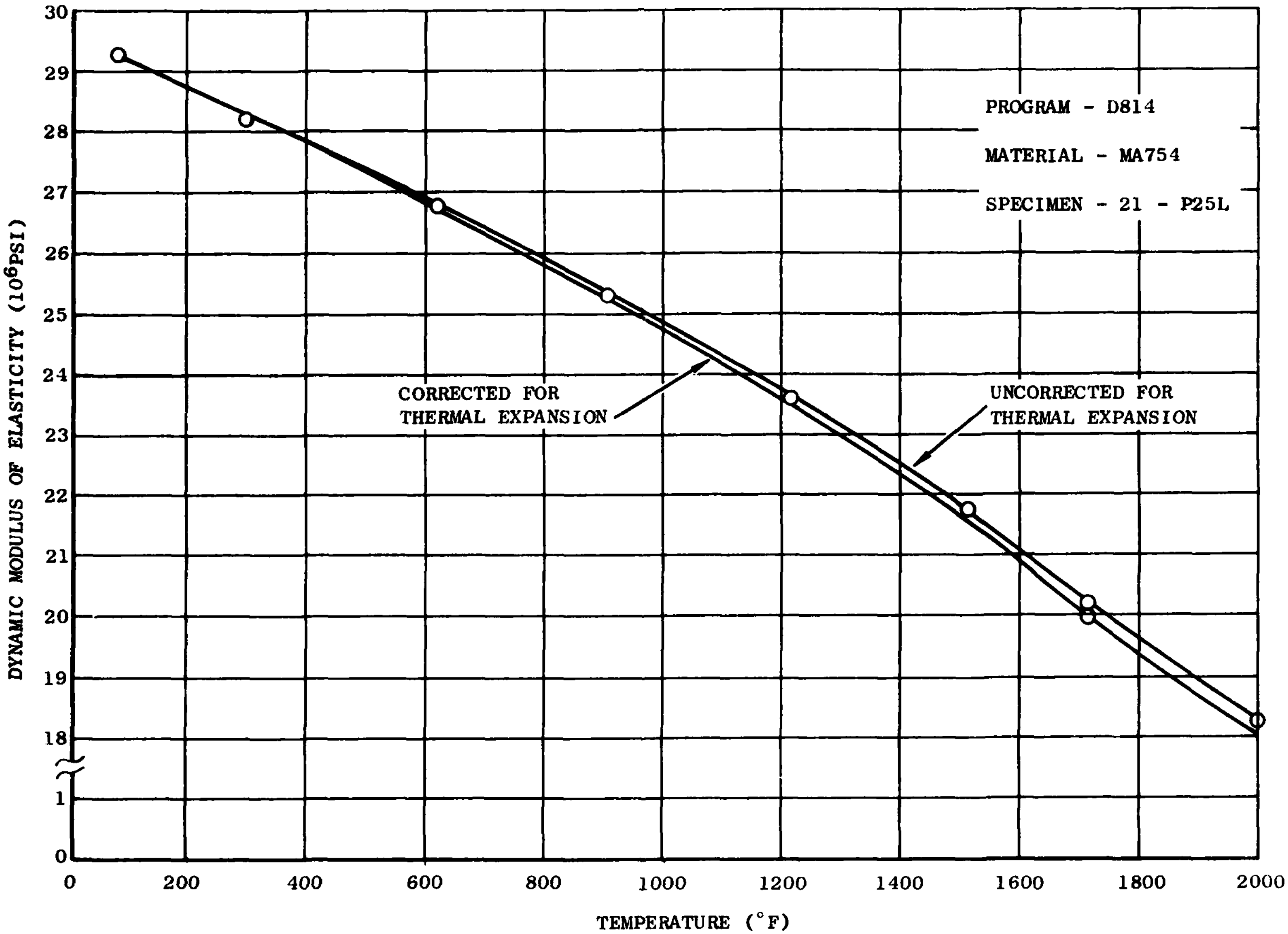


Figure 58. MA754 Specimen 21-LP25L Dynamic Modulus

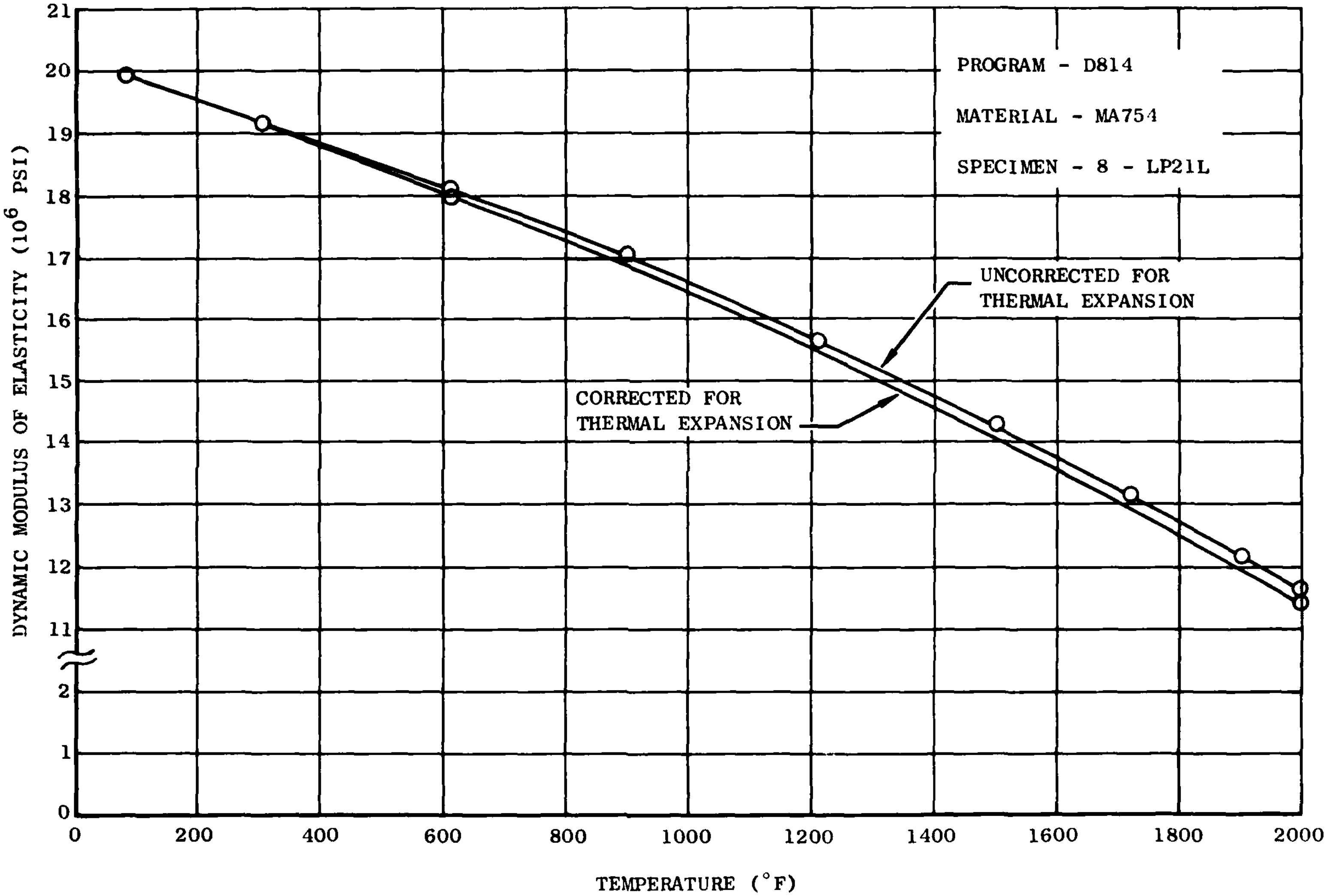


Figure 59. MA754 Specimen 8-LP21L Dynamic Modulus

SECTION VI

PHASE III NEAR-NET SHAPE FINAL COMPONENT MANUFACTURE

In Phase III manufacturing processes were established for producing low cost ODS alloy turbine nozzle vane and band segments from near-net shape components.

6.1 HPT VANE MANUFACTURE

A total of 15 NNS vanes of various process parameters and macrostructures were selected for final machining. The machining was done at Electro-Jet Tool and Die Co., Evendale, Ohio. The initial blank setup on near-net shape vanes is more critical than with the current manufacturing method because of the reduced material envelope. Currently, an MA754 HPT vane is machined from a 1.05" X 3.0" X 3.35" rectangular bar. Approximately 90% of the material is reduced to chips. In setting up the NNS HPT vane for outside contour machining, the first step is to machine the proper reference angle on the bottom of the vane as shown in Figure 60.

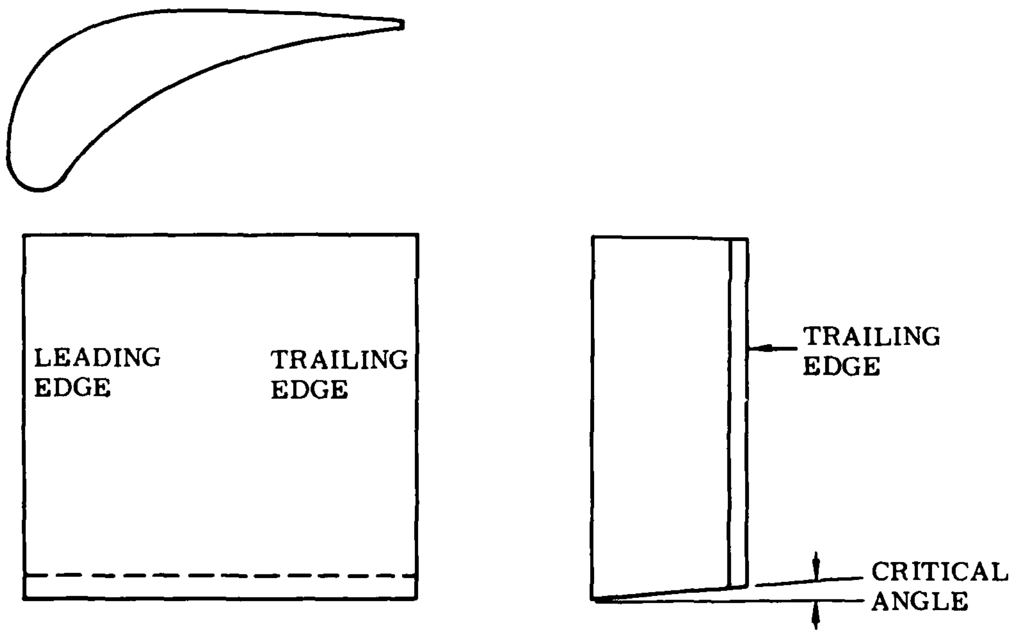


Figure 60. HPT Vane Setup

This bottom machined surface then becomes the locating reference for the contour milling operation. If the locating angle is incorrect, too much material could be removed from one side of the vane resulting in a narrow chord width. Once the reference surface was correctly machined the NNS vanes were processed in the same manner as a conventional MA754 HPT vane except that material removed and machining times were less. Figure 61

AS FORGED NEAR-NET SHAPE
HPT VANE .040" ENVELOPE

PARTIALLY MACHINED HPT
VANE FROM CONVENTIONAL
RECTANGULAR MA754 BAR

Figure 61. NNS and Partially Machined HPT Vanes

shows a partially machined conventional MA754 vane and a NNS vane. Figure 62 shows finished MA754 NNS HPT vanes.

6.2 LPT VANE MANUFACTURE

Six NNS LPT vanes and two spares were final machined at MAL Tool, Vernon, Conn. The LPT nozzle is a 360° one piece unit. Because of this type construction and the vane twist dimensional requirements for a replacement vane are slightly different than for an original assembly vane. Currently, LPT vanes are assembled into the one piece outer band from the inside, then the inner band is assembled and the whole nozzle is brazed together.

In order to assemble NNS vanes into an existing nozzle, the original vanes have to be EDM'ed out for removal through the outer band. Due to the twist in the LPT vane the removal slot in the outer band must be larger than the vane. To provide for reinsertion of a new vane a shoulder was machined on the outboard end of the NNS vanes to facilitate repair brazing. Tooling modifications were required to provide extra material stock at that location. When NNS vanes are assembled into a new nozzle, the vane would be processed in the same manner as a conventional vane. See photo in Figure 63.

6.3 HPT BAND MANUFACTURE

Seven HPT near-net shape bands were selected for final machining at Electro-Jet Tool. Tooling was built to accurately position the NNS inner band for flow path machining. Once this was accomplished the NNS inner band was processed the same as a conventional inner band.

There were no significant problems in manufacturing process of the NNS band components. A photo of a finish machined NNS HPT inner band is shown in Figure 64.

MA754 is a relatively easily machined alloy in either the recrystallized or unrecrystallized condition. The machinability index below compares MA754 with some of the other alloys used in the F101 engine.

MATERIAL	MACHINING RATIO
B1112	100
410 Stainless Steel	37
MA754	24
A286	19
Inconel 718	12
Rene'95 Powder	7
Rene'80	4

B1112 is the base line which all of the other alloys are compared. It has a machining ratio of 100. The lower the number, the harder the alloy is to machine.

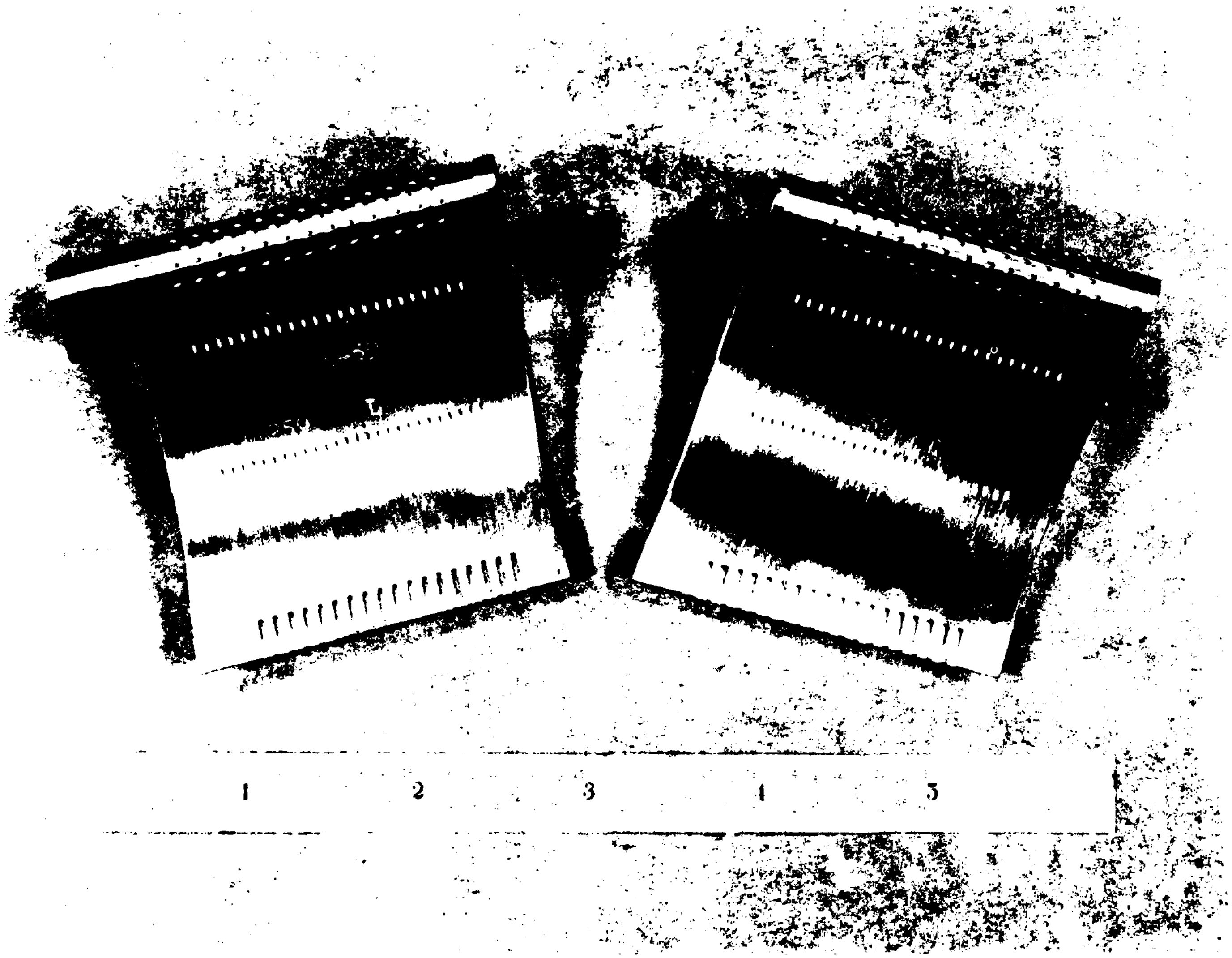


Figure 62. Finish Machined Near-Net Shape HPT Vanes

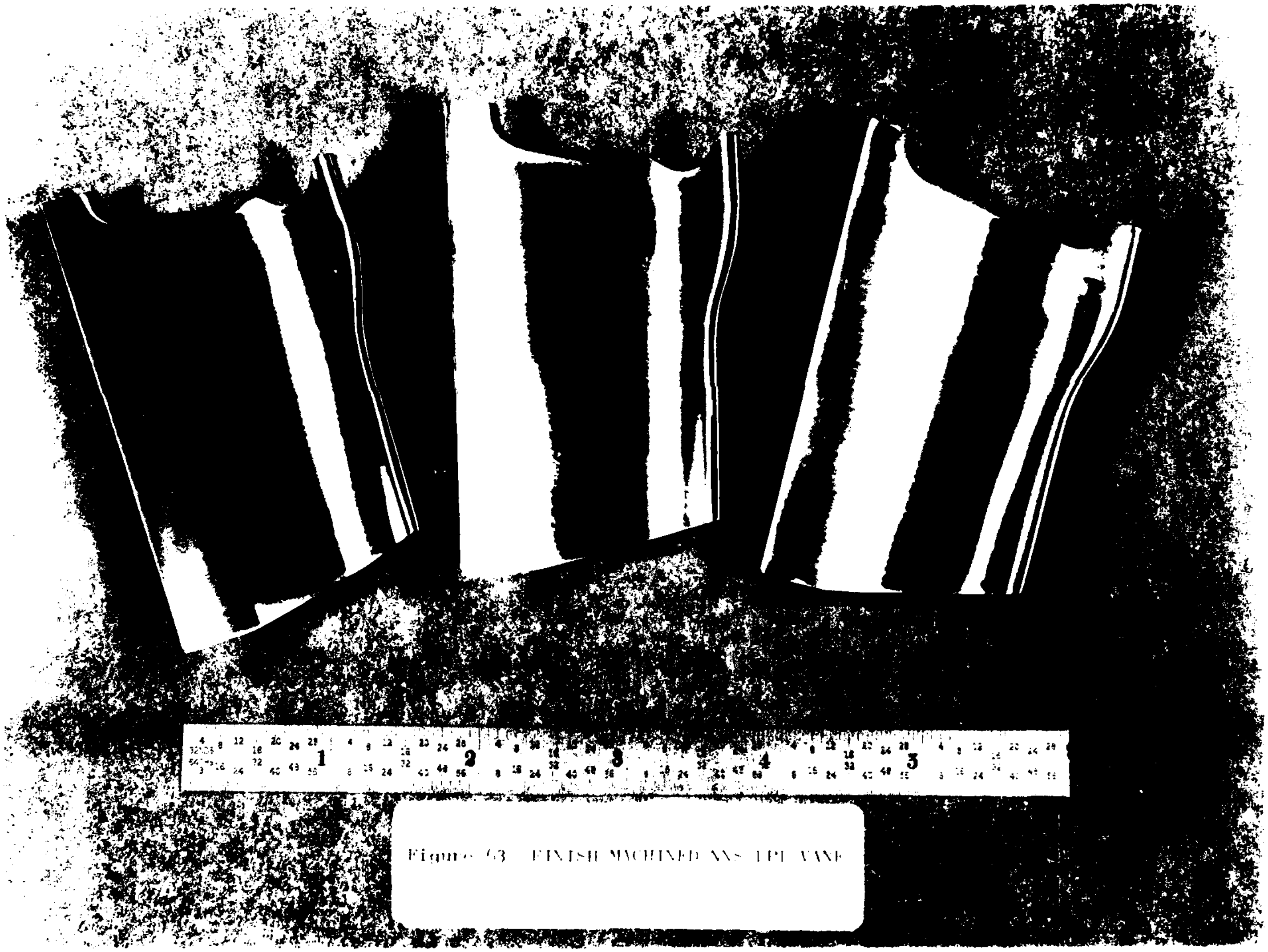


Figure 63. Finish Machined NNS LPT Vane

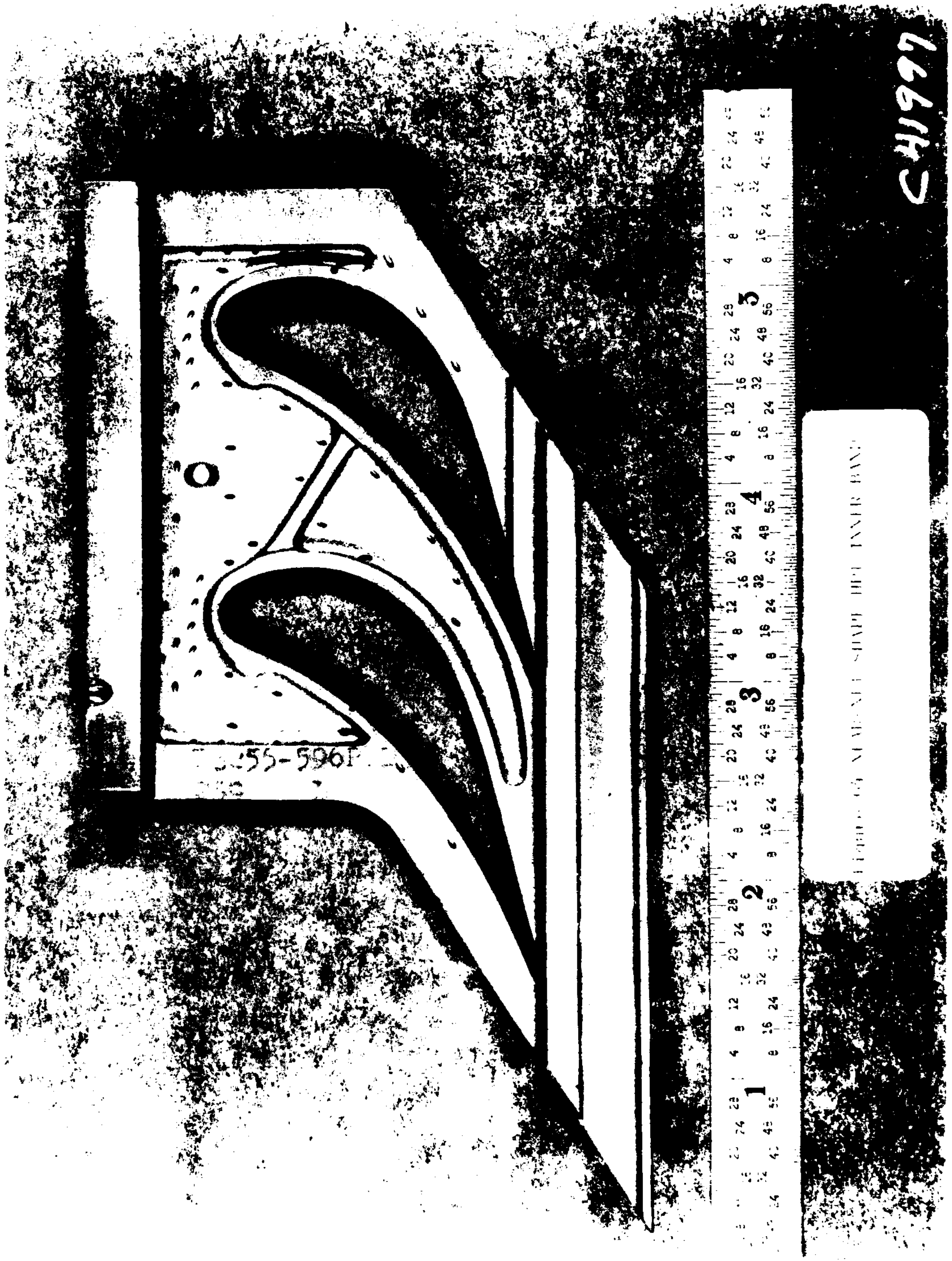
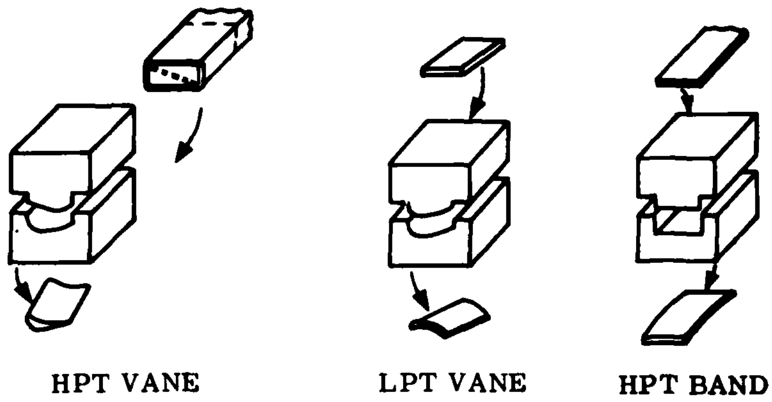


Figure 64. Near-Net Shape HPT Inner Band

SECTION VII

CONCLUSIONS

- Material savings of 50 to 60% can be achieved by implementation of NNS processes:



- Machining savings of 30% can be realized in generating outside contours of vanes and bands through the use of NNS processes.

- NNS processes can utilize commercially available bar stock for input material.

- Mechanical properties of NNS MA754 meet or exceed those of conventionally processed material.

- Microstructures and textures equivalent to conventionally processed MA754 are attainable by NNS processing.

- Isothermal shape rolling (ISR) has potential for near-net working of ODS alloys, but currently available equipment lacks width and squeeze force capability for current HPT vanes.

- The engine test of NNS LPT vanes substantiates the data generated on NNS processed components showing them to be at least equivalent in performance to conventionally manufactured ODS components.

- Although the HPT nozzle segments were not engine tested, all the data generated indicates that the NNS vanes and bands would perform as well as conventionally machined components manufactured from standard ODS material.

- The EDM removal/braze replacement method shows promise as an ODS nozzle repair process.

SECTION VIII

PRELIMINARY MANUFACTURING PROCESS AND PRODUCT SPECIFICATION

8.1 PRELIMINARY MANUFACTURING PROCESS

The preliminary processes outlined below are recommended for the manufacture of MA754 NNS LPT vanes, HPT bands and HPT vanes. The processes are outlined in a flow chart in Figure 65.

(1) Alloy - to be of nominal composition Ni20Cr.3Al.5Ti.6Y_2O_3.

(2) Material Form - material to be procured as unrecrystallized hot finished bar (for HPT vanes) or hot finished plate (for LPT vanes and HPT bands).

(3) Bar and Plate Processing - to be extruded and hot rolled to bar or plate configuration.

(4) Property Requirements - the plate shall be capable of meeting all property requirements specified in the Preliminary Product Specification when given a subsequent recrystallization heat treatment.

(5) Material Condition - to be procured as-rolled (unrecrystallized) and decanned by pickling in 50-50 nitric acid and water solution.

(6) Blank Preparation - NNS HPT band and LPT vane preforms to be within thickness tolerance and the required length for bending. HPT vane preforms to be within the required specified dimensions and configuration for forging.

(7) NNS Processing LPT Vanes and HPT Bands - to be performed in the correct tooling which is maintained at 400°F temperature. Heat unclad, uncoated MA754 NNS preforms to 2050°F in an electric furnace for 15-20 minutes and bend to NNS. Part transfer time and bending time should be kept to a minimum.

HPT Vanes - to be performed in the correct NNS HPT vane forge tooling which is maintained at 400°F. Heat unclad but glass coated to 1750°F - 1800°F in an electric furnace for 15 minutes and forge to NNS. Part transfer and forge time to be kept to a minimum.

(8) Part Cleaning - to be accomplished by grit blasting.

(9) Heat Treatment - stabilize at 2000°F/30 minutes then heat to 2400°F @ 200°F/Hr hold 1 Hr/air cool.

MA754 Powder

Canning

Extrusion

Hot Flat Rolling

Decanning

Blank Preparation

NNS Bending LPT Vanes, HPT Bands

or

NNS Forging (HPT Vanes)

Recrystallization Heat Treatment

Finished Part Machining

Figure 65. Flow Chart of Preliminary Manufacturing Process for Near-Net Shape LPT Vanes HPT Bands and HPT Vanes

8.2 PRELIMINARY PRODUCT SPECIFICATION

The requirements listed below are recommended as a preliminary specification for low cost LPT vanes, HPT bands and HPT vanes made by NNS processing.

1.0 Scope

1.1 Scope - This specification presents requirements for MA754 alloy components.

1.1.1 Classification - This specification contains the following class. Class B (Class A is recrystallized material).

1.2 Definitions - For the purposes of this specification, the following definitions shall apply:

Primary Material - extruded and rolled to required dimension MA754 unrecrystallized bar.

Bend Preform - the individual plate section prepared for bend processing to NNS.

Bend - the hot forming operation to achieve the correct curvature and twist.

Forge Preform - individual bar section prepared by machining for forging.

Forge - the hot forming operation to achieve the correct near-net shape.

NNS - a formed section closely approximating the individual component configuration for high material utilization.

Run - a batch of blanks from the same heat that are NNS processed in one shift.

Recrystallization - formation of the desired grain size, shape and crystallographic orientation by heat treatment.

Class B - hot finished, unrecrystallized MA754 capable of being fully heat treated to meet the mechanical property requirements for Class A (recrystallized) material.

2.0 Applicable Documents

2.1 The following documents shall form a part of this specification to the extent specified herein.

American Society for Testing and Materials
ASTM E139 Conducting Creep, Creep Rupture and Stress Rupture Tests of Metallic Materials

3.0 Requirements

3.1 Chemical Composition, Percent

3.1.1 Material supplied to this specification shall have the following composition as determined in the input powder lot:

Chromium	19.00-23.00
Titanium	0.70 Max.
Aluminum	0.50 Max.
Yttria	0.4-0.8 (1)
Iron	2.50 Max.
Carbon	0.10 Max.
Sulfur	0.015 Max.
Total Oxygen	(2)
Nickel	Remainder

(1) Yttria shall be determined as Yttrium and reported as Yttria.

(2) Shall be reported for information only.

3.1.2 The analysis made by the manufacturer to determine the percentages of elements required in the powder lots by this specification shall conform to the requirements of 3.1.1 and shall be reported in the certificate of test specified herein. An analysis shall be made on each extrusion, after decanning, for the carbon, sulfur and oxygen content, and the percentages of these elements shall conform to the requirements of 3.1.1 and shall be reported in the certificate of test.

3.1.3 An analysis may be made on a sample blank by the Purchaser and the chemical composition thus determined shall conform to the requirements of 3.1.1.

3.2 Material Condition

3.2.1 Material shall be supplied by the primary vendor in the hot finished (unrecrystallized) condition as specified below:

> Material shall be uniform in quality and condition; clean, sound, and free from foreign materials and from internal and external imperfections detrimental to performance of parts.

3.3 Mechanical Properties

3.3.1 Class B: Material to Class B after being fully heat treated, shall meet all of the mechanical property requirements for Class A material as specified on the purchase order.

3.3.2 Stress Rupture

3.3.2.1 Material shall meet the following minimum stress rupture requirements at 2000°F (1093°C):

Test Direction	Class	Stress	Life Hours	Percent Elongation in 4D	Percent Reduction of area
In the direction of hot finishing	B (after recrys-tallization heat treat)	12,000psi	20	(1)	(1)
Long transverse to direction of hot finishing	B (after recrys-tallization heat treat	4,000psi	20	(1)	(1)

(1) Shall be reported for information only.

3.4 Metallographic Inspection

3.4.1 Macro Examination Macroexamination shall reveal a dull matte appearance with no significant differential etching effects across the cross-section.

4.0 NNS Requirements

4.1 The NNS material shall have the same NNS by the Purchaser and the chemical composition thus determined shall conform to the requirements of 3.1.1.

4.1.1 An analysis may be made on a sample NNS by the Purchaser and the chemical composition thus determined shall conform to the requirements of 3.1.1.

4.1.2 Material shall be uniform in quality and condition, clean, sound and free from foreign materials and from internal and external imperfections detrimental to fabrication or to performance of parts.

4.2 Material Condition

4.2.1 Material shall be supplied by the NNS vendor in the recrystallized condition and must meet the requirements of 3.2.1, 3.3.1 and 3.4.

4.3 NNS Configuration

The NNS shall be supplied by the secondary vendor in the condition approximating the LPT vane, HPT inner band and HPT vane configuration. The tolerances of the NNS shall be as specified on the drawing or as agreed upon by the vendor and the Purchaser.

SECTION IX

ECONOMIC ANALYSES NEAR-NET SHAPE PROCESSES

A manufacturing cost comparison of NNS components vs rectangular bar manufacturing is shown in Table 19.

The NNS process offers approximately a 40% cost savings in combined material utilization and part machining. The cost analysis was based on a 250th engine estimate. It includes material, NNS processing and machining costs to finish contour only.

TABLE 19

MA754 MANUFACTURING COST COMPARISON

ITEM	HPT VANE CURRENT METHOD	HPT VANE NNS METHOD	LPT VANE CURRENT METHOD	LPT VANE NNS METHOD	HPT BAND CURRENT METHOD	HPT BAND NNS METHOD
Material Lbs.	3.48#	1.51#	2.25#	.9#	5.4#	2.52#
Material	80%	35%	75%	30%	85%	40%
NNS Processing	NA[1]	8%	NA[1]	9%	NA[1]	5%
Machining Cost (Contour only)	20%	14%	25%	20%	15%	11%
TOTAL	100%	57%	100%	50%	100%	56%

[1] Not Applicable

SECTION X

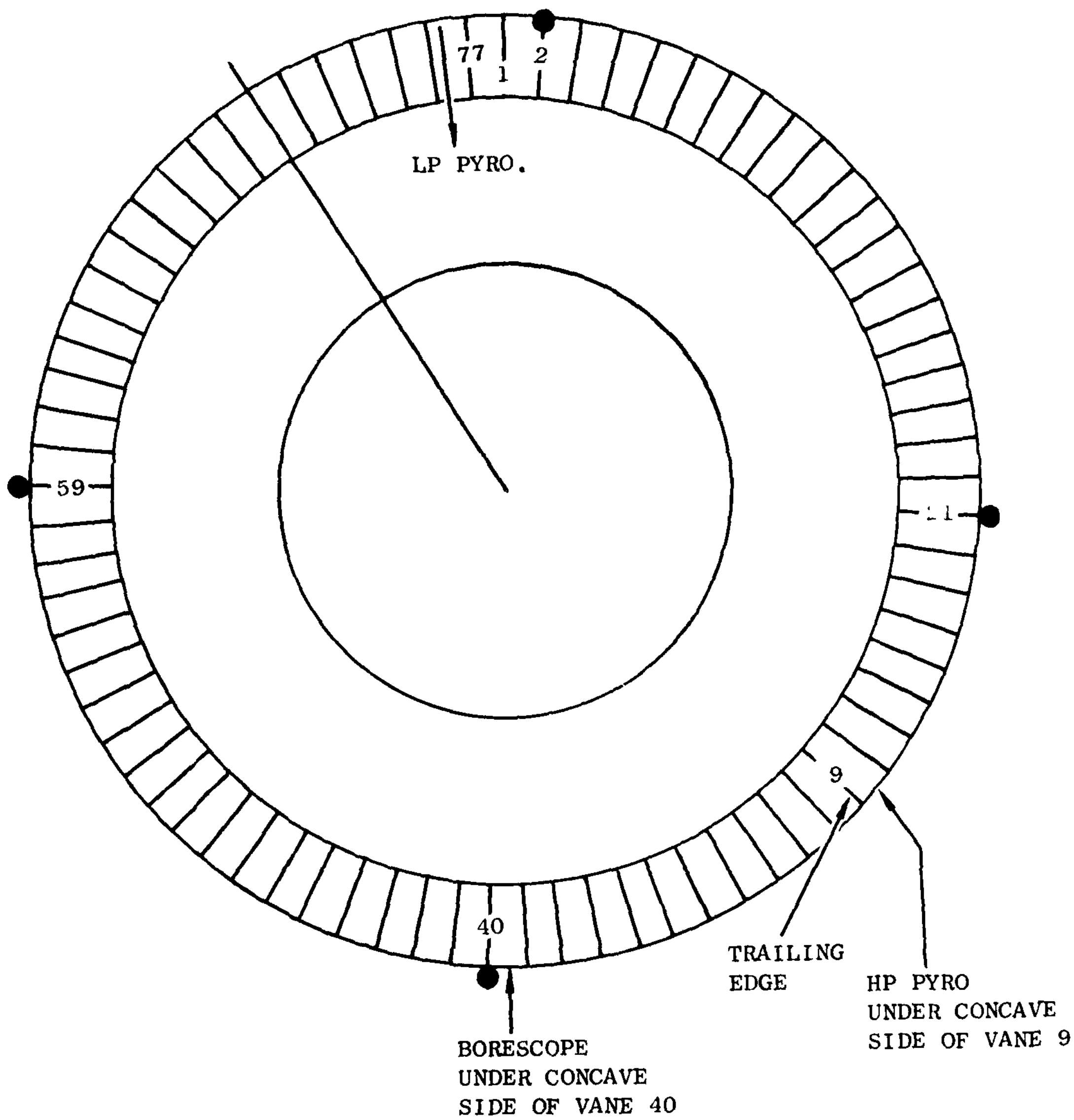
ENGINE TEST RESULTS

10.1 ENGINE TESTING

The F101 low pressure turbine (LPT) nozzle is composed of an inner band, an outer band, and 77 uncooled vanes. The current vane alloy is MA754. The vane operates in an environment such that the principal mechanical stresses are in the engine radial (vane longitudinal) direction. Through-the-wall thermal stresses are low because the vane is uncooled. It is estimated that maximum vane metal temperatures are 1204°C (2200°F) at the 70%-span section of the vane (hot-streak conditions, hot-day takeoff). Stress analyses indicate that the vane is stress rupture limited in the longitudinal direction.

Four near-net shape vanes were assembled into an existing engine run LPT nozzle containing similar ODS vanes produced by conventional methods. The locations of the near-net shape vanes are as shown in Figure 66. A photograph of the assembled nozzle is shown in Figure 67. The low pressure nozzle was installed in an endurance test F101 engine which was run to the test cycles shown in Figure 68. The total running time accumulated on this engine prior to tear down and inspection was 201 hrs. A total of 282 AMT-IV cycles were completed. These AMT cycles encompassed 3629 thermal cycles and 75 hours at maximum power. Following the 201 hrs. of logged running time, the engine was torn down for inspection. The nozzle containing the four near-net shape vanes was in good condition. The NNS vanes did not exhibit any trailing edge bowing or cracking, however, there were indications of surface skin buildup and oxidation. Vane surfaces before and after engine test are shown in Figures 69 and 70.

Since the LPT nozzle had been previously engine run, the conventionally processed vanes exhibited some prior surface oxidation and buildup. The amount and coloration of the buildup was altered by the vacuum heat treat operation required for brazing in the NNS vanes. The oxide buildup is not unusual for hot section components tested at General Electric. The deposit found on these components consists of various metallic oxides. These metallic contaminant particles are suspended in the air in very small quantities, but with the huge volume of air ingested by the engine the small quantities become appreciable deposits.



AFT LOOKING FORWARD
NEAR-NET-SHAPE VANE LOCATIONS
VANES 2, 21, 40, AND 59

Figure 66. Near-Net Shape Vane Locations

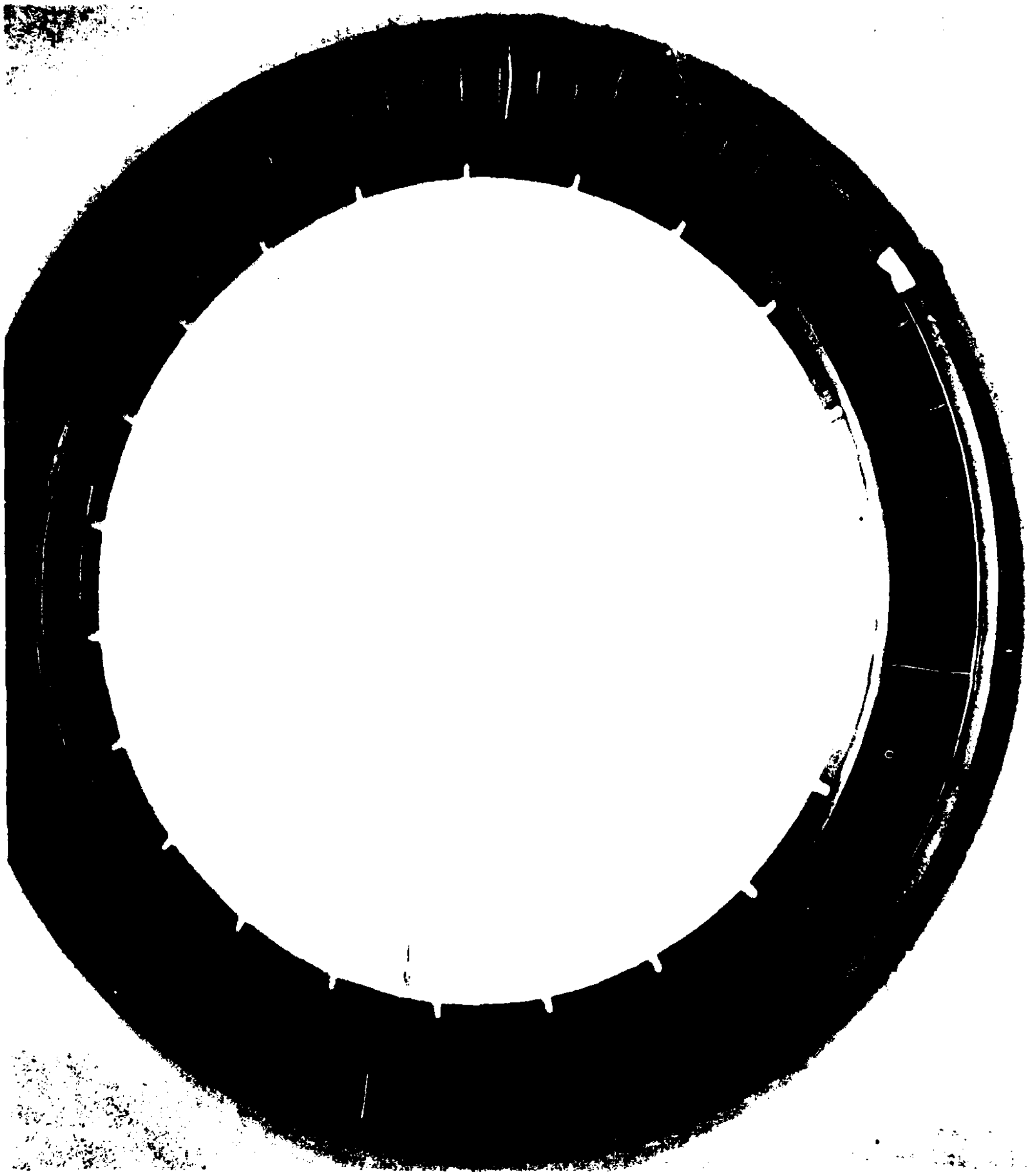


Figure 67. LPT Nozzle Prior to Engine Test

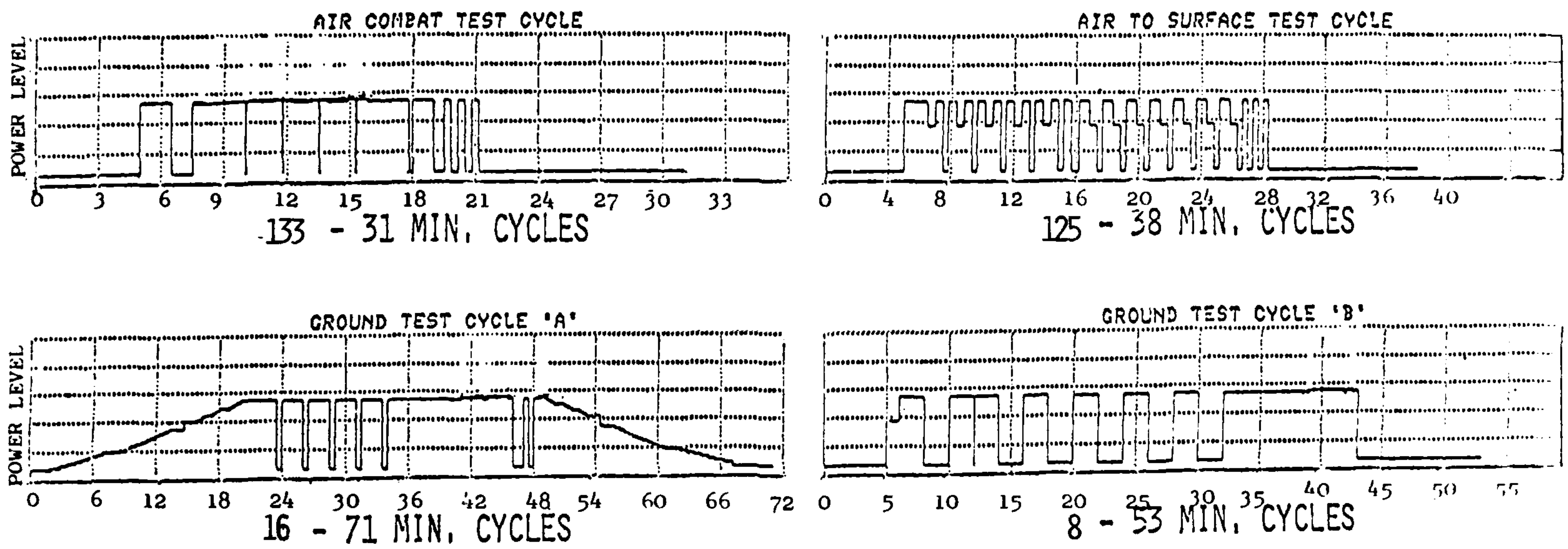
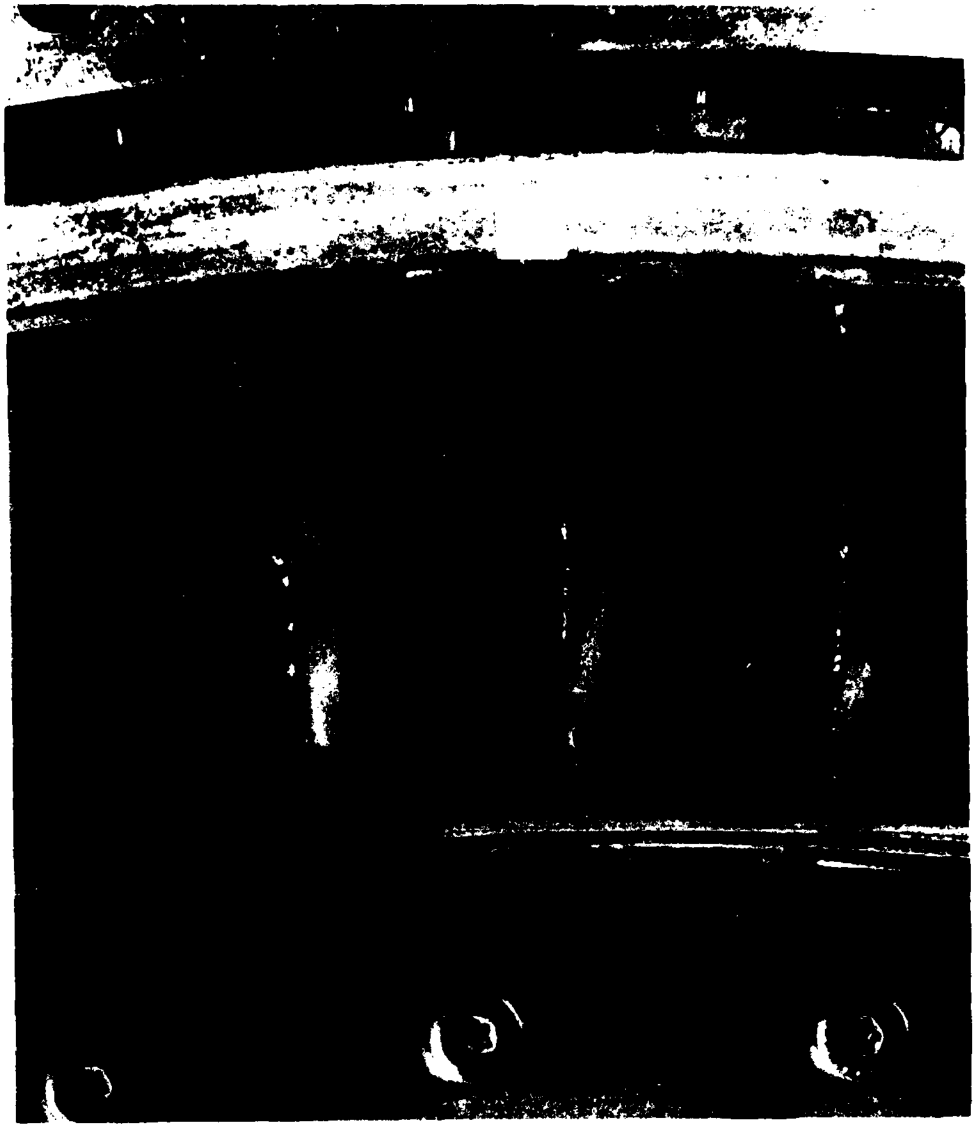


Figure 68. F101 AMT-IV Engine Test Cycles

NEAR-NET SHAPE VANE No. 2 AS BRAZED
PRIOR TO ENGINE TEST

NEAR-NET SHAPE VANE No. 2 AFTER
201 HOURS OF ENGINE TESTING

Figure 69. Engine Test Vane Views - Suction Sides



NEAR-NET SHAPE VANE No. 2 PRESSURE SURFACE
AFTER 201 HOURS OF ENGINE TESTING

Figure 70. Engine Test Vanes Pressure Side

The oxide buildup however, seemed to deposit itself more evenly and smoothly over the surfaces of the previously run vanes. The oxidation buildup on the NNS vanes appeared to be more patchy and flaked off more easily. The contaminant particles apparently adhere less easily to a clean bare metal surface than to a surface which has already been oxidized. It is believed that with continued engine running the oxide buildup conditions will stabilize and the NNS vanes will have the same appearance as previously run vanes.

10.2 HPT NOZZLE SEGMENTS

Near-net-shape HPT nozzle segments consisted of vanes and bands manufactured for engine testing, however the components were not tested because of a design change in the F101 HPT nozzle. The change was from a PV nozzle containing 54 vanes to a RUT nozzle containing 46 larger vanes.

10.3 VANE REPLACEMENT

The LPT nozzle containing the NNS vanes was the first full ring nozzle to undergo an ODS vane retrofit operation. This vane replacement process has potential as an ODS nozzle repair process. Four conventionally manufactured vanes were EDM removed from the nozzle and four NNS vanes were brazed in their places.

10.4 ADDITIONAL MECHANICAL TESTING

Additional stress rupture data not previously reported are presented in Table 20. The data are taken from HPT vanes in the longitudinal direction and LPT vanes in the transverse direction.

TABLE 20

NNS HPT VANES SR RESULTS

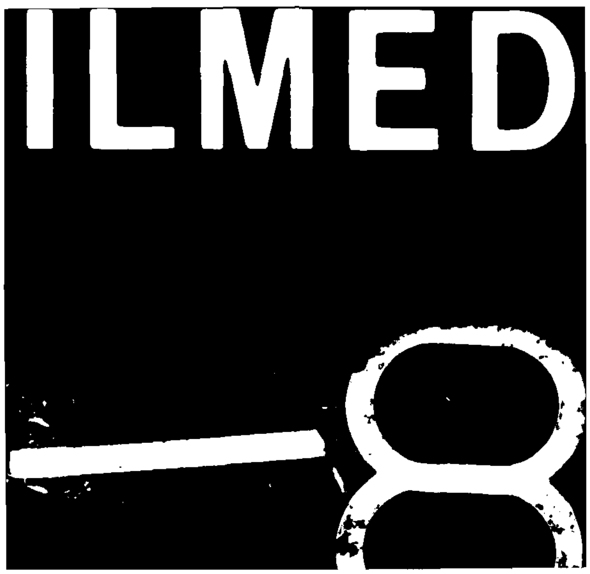
SPEC #	TEST TEMP (°F)	TEST DIRECT.	STRESS KSI	LIFE HRS	LARSEN MILLER PARAMETER	% EL	% RA	REMARKS	PERFORM DESIGN
18-H21L	1800	Long	21	130.7	61.3	9.4	19.1	Gage Fail	D2
36H47L	1800	Long	22	232.5	61.9	---	0.6	Discontinued	D1
1823L	2000	Long	17	257.4	62.0	0.69	2.0	Disc	D2
NNS LPT VANE TRANSVERSE SR RESULTS									
10LP1T	1800	Trans	9	232.0	61.9	0.28	1.9	Disc	
17LP14T	1800	Trans	10	119.8	61.2			Gage Fail	
17LP15T	2000	Trans	5.5	69.1	65.9	1.7	---	Gage Fail	
17LP16T	2000	Trans	5.0	211.3	67.3			Disc	

REFERENCES

1. Perkins, RJ, Bailey, PG "Low Cost Fabrication Development for Oxide Dispersion Strengthened Alloy Vanes" NASA CR135373 (1978)

2. Bailey, PG "Manufacture and Engine Test of Advanced Oxide Dispersion Strengthened Alloy Turbine Vanes" NASA CR135269 (1977)

*U.S.Government Printing Office: 1980 — 657-084/726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